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The following papers were read :—

1. On the occurrence of minerals developed by pneumatolytic action in the Bodmin and Camelford areas : by Messrs. G. Barrow and H. H. Thomas.
2. A protractor for use in constructing stereographic and gnomonic projections : by Dr. A. Hutchinson.
3. Supplementary notes on the mineral kaolinite : by Mr. Allen B. Dick.
4. An attachment to the goniometer for the measurement of lamellated crystals : by H. L. Bowman.
5. Calculation of the chance that the double refraction of a crystal section cut at random shall exceed a particular fraction of the maximum : by Mr. Harold Hilton.

A combination of a quartz-wedge and a gypsum-plate was exhibited and explained by Dr. J. W. Evans. Specimens of minerals and rocks were shown by Messrs. Barrow and Thomas, and protractors by Dr. Hutchinson, in illustration of their papers

MINERALOGICAL SOCIETY.

ABSTRACT OF RECEIPTS AND PAYMENTS FROM JANUARY 1 TO DECEMBER 31, 1907.

[illegible]

Examined and compared with the vouchers, and found correct.

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THE MINERALOGICAL MAGAZINE

AND

JOURNAL OF

THE MINERALOGICAL SOCIETY.

No. 69.

November, 1908.

Vol. XV.

On a protractor for use in constructing stereographic and gnomonic projections of the sphere.

(With Plates III, IV, IV a, and V.)

By A. HUTCHINSON, M.A., Ph.D.

Demonstrator of Mineralogy in the University of Cambridge.

[Read March 17, 1908.]

THE protractor of which an account is given in the following pages is intended to facilitate the construction of stereographic and gnomonic projections of the sphere, especially on the part of students of crystallography. The fundamental properties of these projections, on which its design depends, have long been known, and have been the basis in the past of methods somewhat similar to those about to be described. Any novelty there may be in the device is to be sought therefore in the convenient arrangement of its parts, and in the ease with which it may be constructed and used, rather than in the principles which it embodies. We will consider first the construction of the protractor, then its application in the case of the stereographic and gnomonic projections, and in conclusion will deal with a few points of interest in the history of these projections.

Construction of the Protractor.

The protractor (plate III, fig. 1) consists of a strip of boxwood or other suitable material, of any convenient length and thickness, and of a breadth exactly equal to the radius of the sphere to be projected.

When selecting the radius for this sphere, the length of 10 centimetres naturally suggests itself, and this is doubtless the best unit to choose when it is desired to secure all the accuracy of which a graphical method is capable. It has too the advantage, that stereographic nets based on this unit have been widely employed and are readily obtainable. For students, however, so large a radius is undesirable, and after careful consideration it has been found best to select as unit a radius of 2.5 inches. In constructing a projection on this scale a sheet of paper of only moderate size is required and the necessary circles can in most cases be described with an ordinary pair of compasses; for those of very long radii recourse must be had to beam-compasses, or better, to the curved ruler designed by G. Wulff and E. S. Fedorov. A primitive circle of 5 centimetres radius may be employed if preferred but has been found by experience to be somewhat too small. On the other hand, a radius greater than 10 centimetres will be found inconveniently large. Between these limits any value may be adopted, as for instance, the 7 centimetre radius chosen by the late S. L. Penfield, but, as already stated above, 2.5 inches (6.35 centimetres) has proved to be the most convenient radius for general use.

A protractor adapted to this radius must be 2.5 inches wide and should be about 12 inches long.¹ A zero-line OZ (fig. 1) is drawn across it at right angles to its length, at a distance from one end rather greater than the width of the protractor. Taking as centre the point Z , where this zero-line intersects one edge, the opposite edge ST is graduated by means of a circular dividing engine. The portion of the scale extending from O to T is divided to degrees and the divisions numbered as shown in plate III, fig. 1. The divisions from O to S are exactly the same as

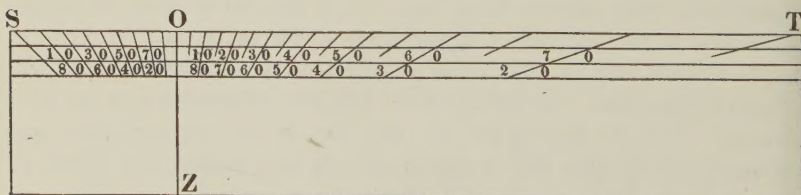


Fig. 1.

those from 0° to 45° along OT , but are numbered differently, each division between O and S representing 2° instead of 1° . A protractor for a

Protractors graduated on boxwood for radii of 2.5 inches and 10 centimetres can be obtained from Mr. W. H. Harling, 47 Finsbury Pavement, London, at a cost of 5s. and 8s. 6d. respectively.

radius of 10 centimetres must be 10 centimetres wide and in this case OT may be divided to half degrees and OS to degrees. For the sake of clearness the finer divisions have been omitted in plate III, fig. 1, as also in text-fig. 1.

From the method of construction it appears at once that the distance from O of any division lying between O and T is numerically equal to the tangent of the corresponding angle, read on the upper row of numbers, when measured with a scale for which the radius of the primitive is taken as unit. Such a scale is provided on the back of the protractor. If the radius of the primitive is 2.5 inches, the scale is divided to fortieths of an inch, while the protractor for use with a primitive of 10 centimetres radius has a millimetre scale. Similarly the distance from O of any division on the scale OS is numerically equal to the tangent of half the angle as read on the lower row of numbers, and the divisions themselves correspond to degrees stereographically projected on a diameter. The use of the protractor will be facilitated if both edges are graduated as shown in plate III, fig. 1, though this is unessential.

Application to the construction of stereograms.

Since the graduation of OT is identical with that of the ordinary rectangular protractor, this scale may be employed in the usual way for setting off angles.

So far as special applications are concerned, the two scales OS and OT taken separately, or in conjunction, enable us to solve with ease the following problems of construction:—

- (1) To project on any diameter the position of a point of which the angular distance from the primitive is known.
- (2) To draw through any projected point a great circle with diameter at right angles to the line joining the given point to the centre.
- (3) To find the pole of any projected great circle; or, in general, to find the point 90° removed from a given point and lying in the same diameter.
- (4) To find the projected position of a face parallel to a face whose projected position is known. In other words, to find the point diametrically opposite to any given point.

- (5) To draw small circles about any point.

These problems will now be considered in detail.

(1) *To project on any diameter the position of a point P (fig. 2) of which the angular distance, θ , from the centre, or $90^\circ - \theta$ from the primitive, is known.*

Describe the primitive circle ZSB . Place the protractor along the given diameter with its zero-point O on the centre of the primitive. The position of P can then be read off directly on the scale OS as shown in fig. 2, where $\theta = 40^\circ$.

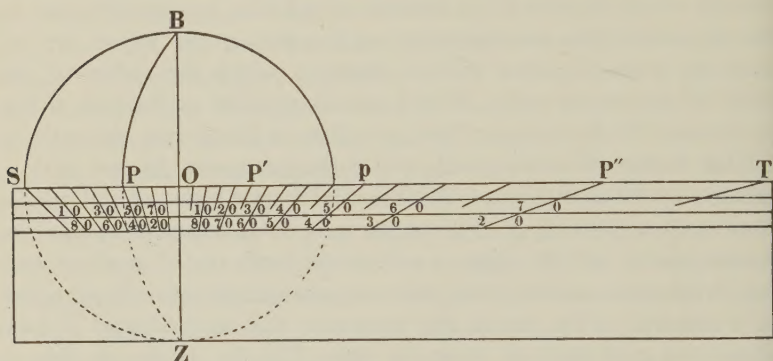


Fig. 2.

(2) To draw through any point P a great circle BPZ perpendicular to that projected in OP .

With the protractor in the same position as above (fig. 2) read the position of P on the scale OS using either row of numbers, and then find a point p , which has the same reading (50° upper row, 40° lower row) on OT , that P has on OS . The circle described with centre p and radius pP passes through B and Z and is the great circle required.

This construction depends on a well-known property of the stereographic projection, namely, that the radius pP of any great circle BPZ is numerically equal to $r \operatorname{cosec} \theta$, where r is the radius of the primitive and θ the north polar distance of P , in other words where $90^\circ - \theta$ is the elevation of the plane of the great circle above the plane of the primitive. Its truth may be demonstrated geometrically in the following simple manner:—

In fig. 3 let P be the projection of a point of which the north polar distance is measured by the angle θ . Draw ZOB perpendicular to OP . Join ZP . Bisect ZP in D and draw Dp perpendicular to ZP cutting PO produced in p . Join Zp . Now p is the centre of a circle passing through the three points Z , P , and B , and represents in the projection the great circle containing P and the diameter ZB . But the angles marked ϕ , viz. PZO , PpD , and DpZ are all equal. Further $2\phi = \theta$, for the eye placed at Z sees N projected at P , and the angle $NOB = \theta$. We have, therefore, $pP = pZ = OZ \operatorname{cosec} 2\phi = r \operatorname{cosec} \theta$.

Now $\operatorname{cosec} \theta = \cot \theta + \tan \frac{\theta}{2}$; and it will be seen from fig. 2 that

$$Op = r \tan (90^\circ - \theta) = r \cot \theta, \text{ and that } OP = r \tan \frac{\theta}{2},$$

hence $pP = r \operatorname{cosec} \theta$, and therefore the circle described with centre p and radius pP is the great circle required.

(3) *To find the pole P' of the great circle BPZ .*

Keep the protractor in the same position as before (fig. 2). Take the reading of P on the scale OS , using the *upper row of numbers*, divide this reading by two, and so find on OT , *upper row of numbers*, the pole P' of the great circle BPZ . In fig. 2 the reading of P is 50° , the corresponding position of P' is therefore at 25° on OT .

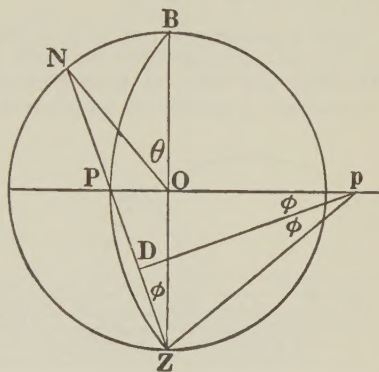


Fig. 3.

The rationale of this process follows at once from a consideration of fig. 2.

The point P is at 40° from the centre, measured stereographically, while P' is at 25° on OT . But 25° on OT correspond to 50° measured on OS and $40^\circ + 50^\circ = 90^\circ$.

(4) *To find the point P'' , the projection of a point diametrically opposite to that projected in P .*

The protractor still remaining in the same position (fig. 2), read the place of P on the scale OS , using this time the *lower row of numbers*. Divide the reading obtained by two and so locate P'' by finding the corresponding reading on the *lower row of numbers* of the scale OT .

In this case again the reason for the procedure employed can readily be deduced from an inspection of fig. 2. The point P is at 40° from the centre measured stereographically, and P'' is at 70° from O on OT . But $70^\circ \times 2 + 40^\circ = 180^\circ$.

(5) *To draw a small circle of given angular radius ϕ° round any point P .*

In crystallographic work two cases present themselves: (i) the point about which the small circle is to be described lies on the primitive, the small circle is accordingly in this case a small vertical circle; (ii) the point is situated within the primitive.

(i) To describe round P (fig. 4) the small circle QOR with angular radius ϕ° :—

Place the protractor along the diameter through P so that the reading for ϕ taken on the scale OS , *upper row of numbers*, falls on the centre C of the primitive. (In fig. 4, $\phi = 50^\circ$.) Mark the position of O , the zero-point of the protractor, and note on OT , *upper row of numbers*, the position of the point p , which has the same reading, ϕ° , on OT that C

has on OS . The circle QOR described with centre p and radius pO is the small circle required.

From a consideration of fig. 4 it will readily be seen that O is the projected position of a point of which the north polar distance is $90^\circ - \phi^\circ$ and which lies, therefore, at ϕ° from the point P on the primitive. Now it can be shown that the radius of a small circle described at an angular distance ϕ° from a point P in

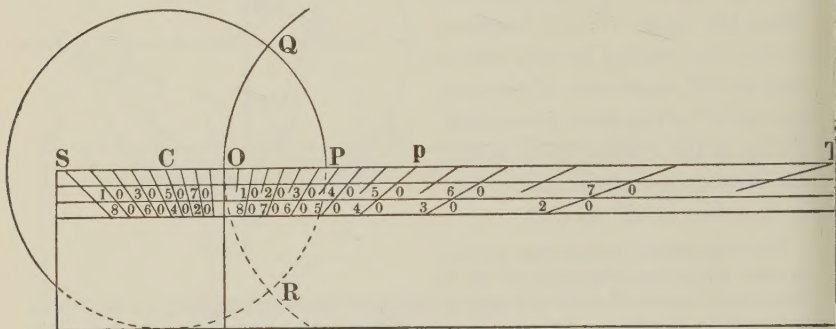


Fig. 4.

the primitive is equal to $r \tan \phi$, where r is the radius of the primitive, for its diameter is equal to $r \tan (45^\circ + \frac{\phi}{2}) - r \tan (45^\circ - \frac{\phi}{2}) = 2r \tan \phi$. But from the construction of the protractor $r = 1$, and $Op = \tan \phi$. Hence, therefore, the circle ROQ described about p with the radius pO is the small circle required.

If the point P lies inside the primitive the method of procedure will vary with its position.

(ii a) The point P lies at the centre of the primitive.

In this case the angular radius ϕ of the small circle is marked off directly from the scale OS and its centre coincides with P .

(ii b) The given point does not lie at the centre of the primitive but occupies some other position, such as P , fig. 5.

In this case the protractor is placed on the diameter through P with its zero-point on the centre of the primitive and the distance of P from the centre is measured with the scale OS . Two points Q and R are now found both at the given distance ϕ from P . The circle through Q and R described with centre p , a point half-way between them, is the small circle required. In fig. 5, P is at 50° from the centre of the primitive and the value of ϕ is 30° . The point Q lies at $50^\circ + 30^\circ = 80^\circ$ from O , while R is at $50^\circ - 30^\circ = 20^\circ$ from O . QR is bisected at p . For making this bisection the scale on the back of the protractor will be found of service.

If owing to the position of P , or to the value of the angle ϕ , the points Q and R lie outside the limits of the semidiameter, it will be necessary to employ the scale OT as well as, or instead of, the scale OS , remembering that each degree read on OT corresponds to two degrees read on OS . This case is also illustrated in fig. 5. Here P' is situated

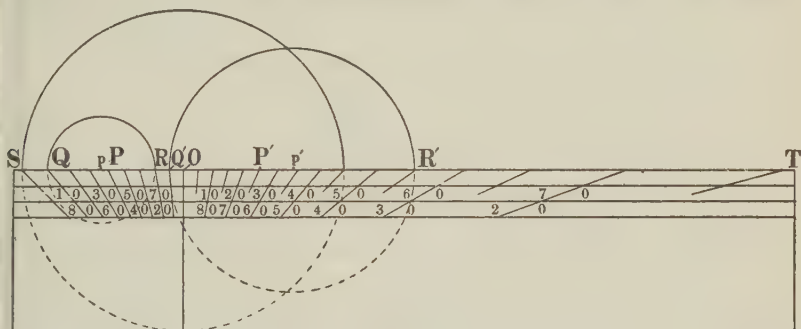


Fig. 5.

at 50° from the centre and $\phi = 60^\circ$. It will be observed that P' , the projection of a point 50° from the north pole, reads 25° on the scale OT . The point Q' at 60° from P' is found by marking off 10° on the scale OS , for $50^\circ + 10^\circ = 60^\circ$. The point R' , also at 60° from P' , is found at 55° on OT , for $\frac{1}{2}(50^\circ + 60^\circ) = 55^\circ$. The centre of the small circle is then obtained by bisecting $Q'R'$ in p' .

The measurement of angles on a stereogram.

When a stereogram has been made it will often be found desirable (i) to measure the angles between two crystal-faces of which the projected positions have been plotted, or (ii) to determine the angles between zones which intersect at a certain point.

The second of these two problems may readily be solved by drawing tangents to the zone-circles at the point where they meet and measuring the angle between these tangents. The solution depends on a valuable property of the stereographic projection, namely its angular truth; in other words the angles between great circles on the sphere are preserved in the projection. A convenient construction is given by S. L. Penfield.¹

The measurement of the angle between two points necessitates the

¹ S. L. Penfield, Amer. Journ. Sci., 1901, ser. 4, vol. xi, p. 19.

construction of the great circle passing through the two points and the determination of the pole of this great circle. The protractor will be found useful in carrying out both these operations. When the great circle and its pole have been determined, the angle between the two points can be found in the usual way by measuring the arc of the primitive cut off by two lines drawn from the pole through the given points. Conversely this construction may be employed to plot the positions of faces lying in a given zone at known distances from some point in the zone.

This problem may be also more rapidly and conveniently solved by means of a stereographic net, as has been pointed out by several writers. Plate IV is a semicircular net for a primitive of 2.5 inches radius, the great and small circles being drawn 2° apart. If a stereogram is drawn on tracing-paper it may be placed above the net with the two centres coincident and the angular distance between any two points may be determined by rotating the drawing above the net about a needle passing through the common centres until the two points lie along the same great circle or evenly between two adjacent ones. The angular distance between the points may then be read off at once by means of the small circles. If, however, the stereogram has been drawn on ordinary paper the problem can be conveniently solved by means of a triangular compass, the three legs of which are placed on the centre of the primitive and on the two points respectively. When set, the compass is transferred to the net, the same leg being placed on the centre in each case, and rotated about this leg until the extremities of the legs which rested on the two given points lie on the same great circle. The angle between them is then read off as before. If such compasses are not at hand, a piece of tracing-paper will answer very nearly as well. It is placed first on the drawing, and the positions of the centre and of the two points are marked on it. It is then transferred to the net. Most convenient of all is a net printed on good transparent tracing-paper, plate IV a, which may be placed directly on the drawing. This will be found very useful, not merely in making measurements on the completed stereogram, but also during the actual construction, as points can be pricked through direct from the net, which may be discarded for a new one as soon as it shows signs of wear.

Application to the gnomonic projection.

Points marked off by means of the protractor using the scale OT' , upper row of numbers, lie at distances from the zero-point numerically

equal to the tangents of the corresponding angles when the radius of the sphere of reference is taken as unity. It follows therefore that the scale OT may be used for projecting gnomonically points of which the north polar distances are given, when the north polar point itself is placed at the centre of the projection. The protractor will also be found of service in determining the angle between any two projected faces as well as the angles between zones.

To find the angle between two faces of which the projections are given.—Let A and B (fig. 6) be the two given points and O the centre of the projection. Join AB . Then AB is the projection of a great circle and represents the zone containing A and B . Draw ON perpendicular to AB or to AB produced. Place the protractor with its zero-point on O and with the scale OT coincident with ON . Read off the position of N on OT , using the upper row of numbers. In NO produced find the point N' which has the same reading on OS , upper row of numbers, that N has on OT .¹ Then $AN'B$ is the angle required. The converse of this construction may be employed to mark off a succession of points lying in the same zone at given angular distances from some point in the zone of which the position is known.

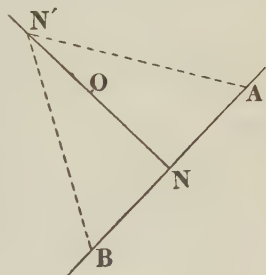


Fig. 6.

The validity of the above construction may be proved as follows:—Let O (fig. 7) be the centre of the projection, C the centre of the sphere, A and B the projections of two faces inclined to one another at the angle BCA . Draw ON perpendicular to BA and join NC . Produce NO to N' , making $NN' = NC$. The angles BCA , $BN'A$ are equal, and the planes CNN' , $AN'B$ are at right angles, while OC is equal to r , the radius of the sphere. Now $CN = r \sec \theta$, where θ is the angle NCO , and

$$\sec \theta = \tan \theta + \tan \frac{1}{2}(90^\circ - \theta).$$

But by construction $NN' = CN$. Hence

$$NN' = r \tan \theta + r \tan \frac{1}{2}(90^\circ - \theta).$$

Now in using the protractor in the manner described above (fig. 6), the distance $ON = \tan \theta$ and $ON' = \tan \frac{1}{2}(90^\circ - \theta)$, for, from the construction of the protractor, distances measured from O along OT are equal to the tangents of the angles read off on the upper row of numbers of that scale, and distances measured from O along OS are equal to the tangents of angles exactly half those read on the lower scale

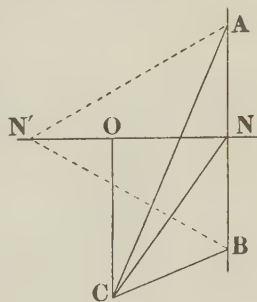


Fig. 7.

¹ The point N' is the 'Winkelpunkt' of V. Goldschmidt, and may be termed the 'angle-point' of N .

of OS , and therefore equal to half the supplements of the angles read on the upper row of numbers. Thus if N reads 60° on OT , N' must be taken at 60° on OS , upper scale. ON' is therefore $= \tan \frac{1}{2}(90^\circ - 60^\circ) = \tan 15^\circ$.

To find the angle between two zones.—Let O be the centre of the projection (fig. 8) and let the projected zones be OF and GF intersecting at F . It is required to find the angle between the zones.

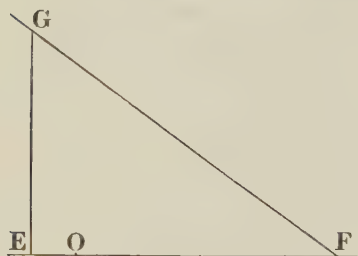


Fig. 8.

Place the protractor along OF with its zero-point on O and read off on the scale OT , upper row of numbers, the position of the point F .

In FO produced find the point E which has the same reading on OS , upper row of numbers, that F has on OT . From E draw EG perpendicular to EF cutting FG in G . Place the protractor along EG with its zero-point at E , then the position of G , as read off on the scale OT , gives the angle between the zone-lines OF and GF .

Proof.—The validity of this very simple construction may be shown as follows:—

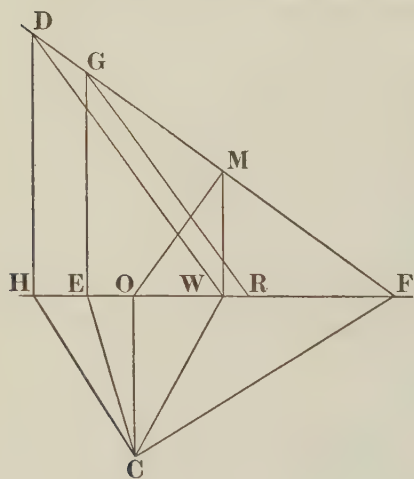


Fig. 9.

—In fig. 9, let O be the centre of the projection and C the centre of the sphere of reference, and let the two zone-lines OF and GF intersect at F . Join FC , and from C draw CH perpendicular to CF . Bisect the angles OCH and OCF by CE and CW , meeting HF in E and W respectively. From H and E draw perpendiculars to HF , meeting FG in D and G respectively. In EF take ER equal to OC , the radius of the sphere. Join DW and GR . The planes DFH and HFC are at right angles, and since CH is perpendicular to CF , F is the pole of the zone projected in HD , and the angle between the zones GF and OF is measured by the angle between the points H and D .

Now from the preceding proposition DWH is the angle between D and H , for by construction the angle OCW is half the complement of the angle OCH , and therefore W is the 'angle point' of H . Similarly, E is the 'angle point' of F . Further, $HC = HW$ and $FE = FC$, for the angles HCW and CWH are equal, as also the angles FEC and ECF . But $DH:GE = HF:EF = HF:CF = HC:CO = HW:ER$.

Hence $DH:HW = GE:ER$, and therefore the angles GRE and DWH are equal.

Now when the protractor is used as described above, the graduations on the scale OT in contact with EG are set off from the centre R . The position of E on the scale OT gives, therefore, at once the angle between the zones.¹

The following is an alternative construction which may be found useful in some cases, though it is a little more troublesome to carry out.

As before, let O be the centre of the projection (fig. 10) and OF and GF the projected zone-lines. Place the protractor along OF with its zero-point on O and read off on the scale OT' , *upper row of numbers*, the position of the point F . Divide this reading by two and so obtain the position of W ('stereographischer Punkt' of V. Goldschmidt). Draw WM perpendicular to OF and join OM . Then MOW is the angle required.

Proof.—In fig. 9, the point W represents the point of the same name in fig. 10. Draw WM perpendicular to OF and join OM . We have to show that the angles DWH and MOW are equal.

Now the angle OCF is bisected by OW , COF is a right angle, and $HW = HC$, therefore

$$\begin{aligned} WF:OW &= CF:CO = CH:OH \\ &= HW:OH = HW + WF:OH + OW \\ &= HF:HW, \text{ and consequently} \end{aligned}$$

$HW:OW = HF:WF$. But $HD:MW = HF:WF$, therefore $HD:HW = MW:OW$, and hence the angles DWH and MOW are equal.

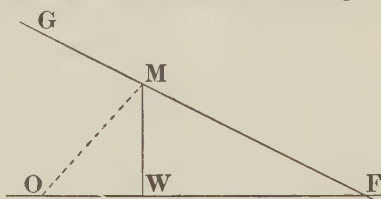


Fig. 10.

In the case considered above one of the zone-lines passed through the centre of the projection, but the construction is equally applicable to the general case in which this does not occur, for it is only necessary to join the point of intersection of the two zones to the centre and proceed as described.

To facilitate the measurement of angles on the completed projections the protractor may be constructed of celluloid. Such a protractor is shown of half-size in plate III, fig. 2. It bears the same graduations as the boxwood protractors but is double their width, and in the case of the scale OT' the graduations for every fifth degree are continued to as near the centre as possible, and between 80° and 85° the graduations for every degree are so continued. A scale of equal parts, 1 div. = 0.01 radius, runs down the centre of the protractor. For the sake of clearness the finer divisions have been omitted in the

¹ This construction may also be utilized to find the angle between two given points. For let H and D be the two points. Find F the pole of the zone HD and join DF . Then find E and proceed as above. Another construction, due to E. S. Fedorov, is given on page 105.

plate. Being transparent the protractor can be used for reading off angles, as well as for performing all the other operations described above.

Another device which will also be found useful is a modified form of triangular compass by the aid of which the problem of finding the angle between any two projected poles in the gnomonic projection may readily be solved graphically with a fair degree of accuracy. This instrument (plate V) consists of two metal bars of rectangular section pivoted together by means of a good sector joint thus enabling the bars to be set at any angle. Metal sliding pieces carrying stout steel pins move freely on the bars and can be clamped in any position. One bar carries two short pins of equal length, the other bar carries one long pin. The pins are so arranged that when the instrument rests on the three points A , B , and O , the three pins are all perpendicular to the plane ABO , and the plane drawn parallel to ABO through the points a and b cuts off a length co from the longer pin, exactly equal to the radius of the sphere of reference. Pins of various lengths can be provided. In practice it is found convenient to have two long ones, in which the distances co are 2.5 inches and 10 centimetres respectively, for use with projections constructed by means of the corresponding protractors.

To find the angle between any two faces all that is necessary is to arrange the instrument so that the point O rests on the centre of the projection while the points A and B fall on the two projected poles. When this is done it is clear that the angle bca is the angle between the two faces, since the points a and b are the projections on the plane oab of two faces inclined at an angle bca and A , B , and O are vertically below a , b , and o . The angle bca can readily be measured, for on inverting the instrument so that the points a , b , c rest on a sheet of paper their positions can be marked and the angle bca read off by a protractor. In this way it is possible to check graphically the results of calculation without drawing any new lines or in any way interfering with a finished diagram.

After the protractor described in the first section of this paper had been designed, and its value tested by actual use, a paper by E. S. Fedorov, entitled 'Die Wichtigkeit der Anwendung des stereographischen Lineals', came to my notice through the medium of an abstract.¹ In this paper, which appeared originally in Russian,² an account is given of an instrument in which the same principles are utilized as those employed by Penfield and myself, although it

¹ Zeits. Kryst. Min., 1908, vol. xlv, p. 89. See also *ibid.*, 1903, vol. xxxvii, p. 141.

² Annuaire Géol. Min. Russie, 1905-1906, vol. viii, p. 26.

differs considerably from the protractor described above in the way these principles are applied, and especially in the arrangement of the scales. One of these rulers, recently obtained from the firm of Fuess, consists of a strip of German-silver, 3 centimetres wide and 41 centimetres long. On one edge is engraved a scale of stereographically projected degrees extending to 90° on the one side of zero, and to 140° on the other; this scale is, in fact, identical with Penfield's scale No. 3, except that it is intended for use with a primitive of 10 centimetres radius, whereas Penfield employed a radius of 7 centimetres. The other edge is occupied partly by a scale of millimetres, 0 to 200, and partly by a scale giving the length of the radii of small circles measured from the primitive. The graduation is beautifully executed, and the instrument is capable of giving very accurate results; it is, however, somewhat costly.

In the same paper several problems of the gnomonic projection are also discussed, and a construction is given for finding the angle between two poles in a zone. As this construction can easily be carried out with the aid of the stereographic protractor, and on account of its elegance and accuracy, deserves to be widely known, it seems desirable to reproduce it here:—

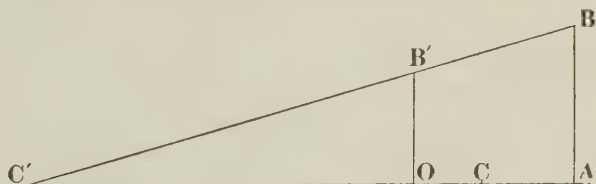


Fig. 11.

Let O (fig. 11) be the centre of the projection, A and B the two projected poles, and OA the perpendicular on AB . Place the protractor along OA with its zero at O and read on OT , upper row of numbers, the angle corresponding to OA , divide by two and so find C . By construction 4, page 97, find C' , a point which in the stereographic projection would be diametrically opposite to C . Join $C'B$. Through O draw OB' parallel to AB . Now place the protractor along OB' and read off on the upper scale of OT the position of B' . The reading so obtained is the angle between the faces projected at A and B .

Historical Appendix.

The stereographic and gnomonic projections of the sphere have proved such valuable aids in the study of crystallography that nearly every textbook of this subject deals with their construction in more or less detail. Naturally, however, the treatment in such works is concerned more with the practical application of these projections to the problems of crystallography than with their general properties, and it is thought, therefore, that a few notes of a historical character may not be devoid of interest.

Our knowledge of the *stereographic projection* we owe to Ptolemy, and it seems probable that he in his turn was indebted to the works of

his great predecessor Hipparchus, whose writings on this subject are, however, no longer extant. From Ptolemy the knowledge of the projection appears to have passed to the Arabs, and was by them handed down to the mathematicians of the middle ages. As a convenient and easily constructed method of projecting the sphere on a plane it found wide application under the name of *planisphaerium* in the manufacture of astrolabes, and received much attention at the hands of a numerous band of writers. Among these the only authors who merit our attention are Jordanus, whose '*Planisphaerium*' was written at the beginning of the thirteenth century, and Fredericus Commandinus,¹ to whom we owe the first satisfactory Latin translation of Ptolemy's work to appear in print. Accompanied by a commentary and by the '*Planisphaerium*' of Jordanus, it was printed by Aldus and appeared in Venice about the middle of the sixteenth century. The end of the same century saw the publication of the monumental work of C. Clavius² on the astrolabe. This closely printed octavo of 759 pages is very rare, but the work was reissued in the collected edition of the mathematical writings of Clavius which appeared at Mainz at the beginning of the seventeenth century.³

The next work of originality and merit is that of Adrianus Metius.⁴ In his '*Primum Mobile*' he describes the construction of the stereographic projection, and points out how it may be used for the graphical solution of spherical triangles. His work is of special interest to us, because he was evidently acquainted with the properties of the projection on which depend the methods of finding the centres of great circles and of small vertical circles employed in the protractor described above. In the absence of formal proofs this may be concluded from the fact that he prints tables giving the lengths of the radii of these circles. The tabulated number in the case of great circles is the secant of the angle of elevation of the great circle above the plane of the primitive, and in the case of small circles, the tangent of the angular radius of the small circle. In the tables the numbers are given for every degree and to six places. To Metius we owe also a stereographic net or projection of meridians and parallels on the plane of a meridian. The net which accompanies his book was engraved by Guilielmus Blaeuw and bears date 1624. It is 29.2 centi-

¹ '*Ptolemaei Planisphaerium.*' Venetiis, 1558.

² '*Christophori Clavii Bambergensis e Societate Iesu Astrolabium.*' Romae, 1593.

³ '*Christophori Clavii Bambergensis e Societate Iesu Operum Mathematicorum Tomus Tertius.*' Moguntiae, 1611.

⁴ Adrianus Metius, '*Primum Mobile.*' Editio nova. Amsterdami, 1633.

metres in diameter and gives the meridians and parallels to every degree. For accuracy and delicacy of execution it will bear comparison with good modern work. It was used by Metius for the working out of astronomical problems and for the solution of spherical triangles. It is interesting to notice that Metius appears to have experienced difficulty in drawing circles of great radii, and it would seem that he contented himself with the approximation to a flat circular arc afforded by a portion of an ellipse, for he figures and describes an instrument for drawing such arcs identical in principle with the elliptic trammel in use at the present day. The only other writer of this period to whom reference need here be made is Franciscus Aguilonius¹ to whom is due the introduction of the name 'stereographic' for this projection.

In the eighteenth century the use of the globes and the projection of the sphere were favourite subjects with mathematical writers in this country, and the works of J. Harris,² Jo. Wilson,³ and Charles Leadbetter⁴ may still be consulted with advantage. As a knowledge of the use of the globes ceased to be an essential part of a liberal education the demand for such treatises gradually declined. Among the last and best we find a work by W. Emerson⁵ in which the properties of the orthographic, stereographic, and gnomonic projections are clearly discussed. A German work of merit belonging to the same period is that of Georg Simon Klügel.⁶ In recent times a formal treatise on the stereographic projection has been published by E. Reusch,⁷ and sections dealing with its general properties are to be found in the textbooks devoted to map-projection, as for instance those of A. Germain,⁸ G. J. Morrison,⁹ C. F. Close,¹⁰ and K. Zöppritz.¹¹

¹ 'Francisci Aguilonii e Societate Iesu Opticorum Libri Sex.' Antverpiæ, 1613. (See Book vi, p. 573.)

² J. Harris, 'Elements of Plain and Spherical Trigonometry.' London, 1706.

³ J. Wilson, 'Trigonometry with the Doctrine of the Sphere.' 2nd edit. Edinburgh, 1724.

⁴ C. Leadbetter, 'A Compleat System of Astronomy.' London, 1728.

⁵ W. Emerson, 'The Projection of the Sphere.' 2nd edit., London, 1769.

⁶ G. S. Klügel, 'Geometrische Entwicklung der Eigenschaften der stereographischen Projection.' Berlin und Stettin (Friedrich Nicolai), 1788.

⁷ E. Reusch, 'Die stereographische Projection.' Leipzig, 1881.

⁸ A. Germain, 'Traité des Projections.' Paris [1866?].

⁹ G. J. Morrison, 'Maps, their Uses and Construction.' 2nd edit., London, 1902.

¹⁰ C. F. Close, 'A Sketch of the Subject of Map Projections.' London, 1901.

¹¹ K. Zöppritz, 'Leitfaden der Kartenentwurfslehre.' New edition by A. Bludau, Leipzig, 1899.

As is well known, the special value of the stereographic projection depends in the first place on the property that any circle on the sphere is projected either as a circle or as a straight line, and secondly, on its angular truth. How far these properties in their general form were known to Ptolemy is difficult to discover; in all probability he was unaware of the second and acquainted with the first in special cases only. That circles are projected as straight lines or circles was known to Jordanus, and was proved for all possible cases and at great length by Clavius in the work referred to above.

The history of the second property is involved in considerable obscurity. The credit of its discovery has been freely attributed to Charles Leadbetter. A proof of the property is certainly contained in his 'Compleat System of Astronomy' and we read in the 'Dictionary of National Biography':—'He gave in this work perhaps the earliest demonstration of a well-known property of stereographic projection.' The ultimate authority for this ascription appears to be J. B. Delambre, who in his 'Histoire de l'Astronomie au dix-huitième Siècle', Paris, 1827, p. 88, makes the following reference to the 'Compleat System':—'La seule chose qui m'ait paru digne d'être extraite de ces deux volumes, est la démonstration du second théorème général de la projection stéréographique, c'est-à-dire de l'égalité des angles sur la sphère et sur la projection. Cette démonstration est la plus ancienne que je connaisse; mais elle ne paraît ni la plus claire ni la plus complète. Essayons de l'éclaircir et de la compléter.'

Leadbetter is not, however, the only Englishman to whom this credit has been assigned, for in the 'Dictionary of National Biography', under Robertson, John (1712–1776), we find:—'He is said to have been the first to discover the theorem that in stereographic projection the angle between two circles on the sphere equals the angle between the two circles on projection.' This time the authority is Chasles, 'Aperçu Historique . . . des Méthodes en Géométrie,' Bruxelles, 1837, p. 517. Referring to this property he says:—'Ce beau théorème n'a pas été aperçu par Ptolémée ni par Jordan. L'ouvrage le plus ancien, à la connaissance de M. Delambre, où il se trouve, est le traité de navigation de Robertson (1754). (Voir Traité d'astronomie, t. iii.)' Turning now to Delambre's 'Astronomie Théorique et Pratique', Paris, 1814, vol. iii, p. 674, we find the following passage:—'La première propriété paraît n'avoir pas été ignorée des Grecs, quoiqu'elle ne soit expressément mentionnée ni par Ptolémée, ni par Synésius, dans sa Lettre sur l'Astrolabe. La seconde paraît d'une date beaucoup moins ancienne; je

l'ai vainement cherchée dans le gros *Traité de Clavius*, dans celui de *Stofflerinus* et dans *Bion*. Elle est énoncée dans le *Dictionnaire de Mathématiques de Saverien*, Paris, 1753, et démontrée par *Robertson*, dans ses *Éléments de Navigation* (1754).'

That *Robertson* was not the originator of the proof was, however, recognized by *Delambre* himself, for in the interval which elapsed between the publication of his '*Astronomie*' in 1814 and his death in 1822 he had become acquainted, as we have seen above, with the writings of *Leadbetter*. But, although he was unable to find an earlier reference to the theorem, he was not disposed to attribute the credit of its discovery unreservedly to *Leadbetter*, for in his '*Histoire de l'Astronomie au dix-huitième Siècle*', p. 90, he says:—'Nous avons la preuve que la seconde propriété de la projection stéréographique était connue dès l'an 1728, et que la date est probablement plus ancienne encore; car nous ne croyons pas que *Leadbetter* en soit l'auteur. Il n'y a pas non plus grande apparence qu'on soit parvenu à ce théorème par les raisonnemens de cet astronome.' As a matter of fact, *Delambre* was perfectly justified in maintaining this cautious attitude, for a proof identical with *Leadbetter's* is to be found in the works of *Wilson* (1724) and of *Harris* (1706) cited above, and it was evidently common knowledge at the time. It seems, indeed, highly probable that all these writers were indebted either directly or indirectly to an important paper published by *Edmund Halley*¹ in the *Transactions of the Royal Society* in 1695–1697.

This paper, which is of considerable interest in the history of navigation, is entitled '*An Easie Demonstration of the Analogy of the Logarithmick Tangents to the Meridian Line or sum of the Secants: with various Methods for computing the same to the utmost Exactness*'. *Halley* says:—'For this Demonstration it is requisite to premise these four *Lemmata* . . . Lem. II. In the *Stereographick Projection*, the Angles, under which the Circles intersect each other, are in all cases equal to the Spherical Angles they represent: Which is perhaps as valuable a property of this *Projection*, as that of all the Circles of the Sphere thereon appearing Circles: but this not being vulgarly known, must not be assumed without a *Demonstration*.' The demonstration *Halley* gives is that found in the works already quoted and need not be reproduced here. At its conclusion he says:—'This *Lemma* I lately received from Mr. *Ab. de Moivre*, though I since understand from Dr.

¹ *Phil. Trans.*, 1695–1697, vol. xix, No. 219, p. 202.

Hook that he long ago produced the same thing before the *Society*. However the demonstration and the rest of the discourse is my own.' All efforts to trace back the theorem to a date antecedent to Halley's paper have so far proved unsuccessful. To apportion the credit of its discovery between Halley, de Moivre, and Hook, is a delicate task, but we shall probably hardly do wrong if we assign to Halley the lion's share.

If we consider now the application of this projection to the special problems of crystallography, we find that it has been freely employed in this study ever since F. E. Neumann¹ drew the attention of crystallographers to its advantages in the first quarter of last century. The work of W. H. Miller² in this direction and the beautiful stereograms drawn by A. Des Cloizeaux³ are well known.

Quite lately the method has received further development at the hands of E. S. Fedorov⁴ and G. Wulff,⁵ who share the credit of the introduction of the flexible ruler so useful in drawing arcs of circles of very long radii. Both these authors have, moreover, published stereographic nets for a primitive of 10 centimetres radius, and both have pointed out how the triangular compass may be used with advantage in making measurements. A smaller net for a primitive of 5 centimetres radius was issued by Benno Hecht⁶ in 1893, and an extension of this beyond the boundary of the primitive has recently been published by E. Sommerfeldt⁷ and employed by him in the construction of crystal figures. This projection has also been the subject of an important paper by V. Goldschmidt,⁸ in which are set forth methods of dealing with the data furnished by the two-circle goniometer.

It is, however, to the writings of the late S. L. Penfield⁹ that we must turn for the most exhaustive exposition of the various constructions employed in solving graphically the problems presented by crystals. To him we owe stereographic nets printed on transparent celluloid for use in measuring completed drawings as well as the introduction of

¹ F. E. Neumann, 'Beiträge zur Krystallonomie.' Berlin and Posen, 1823.

² W. H. Miller, 'A Treatise on Crystallography,' 1839. 'Mineralogy,' 1852.

³ A. Des Cloizeaux, 'Manuel de Minéralogie,' vol. i, 1862, vol. ii, 1874-1893.

⁴ E. S. Fedorov, Zeits. Kryst. Min., 1893, vol. xxi, p. 617, and 1903, vol. xxxvii, p. 188.

⁵ G. Wulff, *ibid.*, 1893, vol. xxi, p. 253, and 1902, vol. xxxvi, p. 14.

⁶ B. Hecht, 'Anleitung zur Krystallberechnung.' Leipzig, 1893.

⁷ E. Sommerfeldt, Zeits. Kryst. Min., 1906, vol. xli, p. 164.

⁸ V. Goldschmidt, *ibid.*, 1899, vol. xxx, pp. 260-271.

⁹ S. L. Penfield, Amer. Journ. Sci., 1901, ser. 4, vol. xi, pp. 1-24 and 115-144; see also vol. xiii, pp. 245-275 and 347-376, vol. xiv, pp. 249-284.

sheets of paper specially designed for the construction of stereograms. On these sheets are printed circles of 7 centimetres radius divided into degrees, together with four scales. Of these, the first two give the radii of great and small circles respectively, while the third is a scale of stereographically projected degrees extending from 0° to 90° on one side of the centre, and on the other beyond the limits of the primitive up to 145° . The fourth scale is one of equal parts where each division is a one-hundredth part of the radius. These scales are based on the same principles as have been utilized above, and if the special sheets are not at hand all Penfield's constructions can be carried out with ease by means of the stereographic protractor. Indeed, a protractor graduated for a radius of 7 centimetres will be found more convenient for use with Penfield's circle than the scales printed on the sheets, as it can be placed on the drawing and points pricked off direct.

In concluding this section we may mention that a paper by J. G. Goodchild,¹ entitled 'Simpler methods in crystallography', contains some useful hints on the construction of projections, while those interested in the history of the subject will find much information in A. von Braunmühl's² 'History of Trigonometry' and in a paper by S. Haller³ in which the methods of Clavius are succinctly set forth.

Gnomonic projection.—This projection has a much shorter authentic history than that we have just discussed, for though Ptolemy has been credited with a knowledge of it by Delambre, the grounds for this attribution appear to be somewhat slender, and we must seek the earliest account of it in the 'Prospectiva nova Coelestis' of Christophorus Grienberger published at Rome in 1612. It was first used in the construction of star maps, a purpose for which it is still employed. A celestial atlas on this projection was issued at Paris in 1674 by Ignatius Gaston Pardies, and reduced copies of these maps are to be found in the 'Cosmography' of Sir Jonas Moore.⁴ A good account of the essential properties of the projection is given by W. Emerson,⁵ and interesting information as to its early history may be found in the tract written by A. de Morgan⁶ to

¹ J. G. Goodchild, Proc. Roy. Phys. Soc., Edinburgh, 1897-1901, vol. xiv, pp. 323-359 and 403-434.

² A. von Braunmühl, 'Vorlesungen über Geschichte der Trigonometrie.' Leipzig, 1900.

³ S. Haller, 'Bibliotheca Mathematica.' 1899, vol. xiii, p. 71.

⁴ J. Moore, 'A New Systeme of the Mathematicks.' London, 1681. (See 'Cosmography,' p. 162.)

⁵ W. Emerson, loc. cit.

⁶ A. de Morgan, 'An Explanation of the Gnomonic Projection of the Sphæra.' London, 1836.

accompany some beautiful maps, terrestrial as well as celestial, issued by the Society for the Diffusion of Useful Knowledge, and based on a sphere of reference of 5 inches radius. At the present day charts on this projection are issued by the American Admiralty.

The applications of the gnomonic projection to crystallography have been so admirably dealt with by V. Goldschmidt¹ that we need not do more than call attention here to a few recent publications on the subject. In this country H. A. Miers,² G. F. H. Smith,³ J. W. Evans,⁴ and H. Hilton,⁵ have all made important contributions to our knowledge. To the last we owe a gnomonic net, which may be employed in the same way as the stereographic nets already described, while G. F. H. Smith has published a table, which will be found to facilitate the plotting of crystal measurements made with the two-circle goniometer. On the continent, E. S. Fedorov has written much on the subject, and we owe to him several ingenious graphical methods, one of which was given above.

Orthographic projection.—By dropping perpendiculars on the equatorial plane from points on the sphere, we obtain the orthographic projection, a method of representation which shares the antiquity of the stereographic projection, and one which, under the name of the *analemma*, was well known to the mathematicians of the middle ages. Employed by them in the solution of astronomical problems, its use in modern times has been almost entirely confined to the construction of maps of the moon. It is ill adapted to the purposes of crystallography, but it may nevertheless claim brief mention here, for F. E. Wright⁶ has recently pointed out that it is suited to the delineation of the interference-figures afforded by crystals when viewed in the polarizing microscope, and he has published an orthographic net. Such a net has also been prepared by the authorities of the Stonyhurst Observatory. It is 6 inches (= 15.24 centimetres) in diameter, and though designed to assist in the study of sun-spots, it might quite well find application in the manner suggested by Wright.

¹ V. Goldschmidt, 'Ueber Projection und graphische Krystallberechnung,' Berlin, 1887. See also, Zeits. Kryst. Min., 1890, vol. xvii, p. 97, and 1892, vol. xx, p. 143.

² H. A. Miers, Min. Mag., 1887, vol. vii, p. 145.

³ G. F. H. Smith, Min. Mag., 1903, vol. xiii, pp. 309-321.

⁴ J. W. Evans, Min. Mag., 1906, vol. xiv, p. 149.

⁵ H. Hilton, Min. Mag., 1904, vol. xiv, pp. 18-20, 1905, vol. xiv, 99-103, 104-108.

⁶ F. E. Wright, Amer. Journ. Sci., 1907, ser. 4, vol. xxiv, p. 321.

*On the occurrence of metamorphic minerals in calcareous rocks in the Bodmin and Camelford areas, Cornwall.*¹

By G. BARROW and H. H. THOMAS, M.A., B.Sc.

[Read March 17, 1908.]

CORNWALL has long been famous for the occurrence of certain minerals, found in the neighbourhood of the great granitic intrusions, that are rare in, or absent from, the aureoles of metamorphism surrounding the granites of many other regions. It is now generally recognized that these minerals have been produced by the action of certain heated gases on the rocks they penetrate along cracks and fissures; but the exact age of this type of alteration is not so well known. It is often held to be contemporaneous with the thermo-metamorphism produced by the granite, and rocks containing these minerals are included in the description of the 'contact rocks' surrounding the granite. This view, however, is not correct; while the gases and the granite clearly have a common deep-seated source, the greater part of the gaseous intrusions are not only later than the granite, but later also than many of the elvans that actually cut the granite and have chilled margins. Further, the finest illustrations of this type of alteration do not occur close to the granite, but at a distance, in the best case, of at least two miles from its margin, where the ordinary killas shows no trace of 'contact-action'. Lastly, this action often profoundly modifies the already 'contact-altered' rocks, and specially fine illustrations of this phenomenon have been met with by Mr. W. A. E. Ussher in the South Brent area, near the Dartmoor granite.

Recent investigations have also shown that the species of minerals produced is far more rigidly dependent on the nature of the material penetrated by these gases than is generally supposed: thus over a considerable area a vast number of small patches of banded killas have been tourmalinized, almost every particle of material other than quartz being absorbed in the formation of tourmaline. So far as is known, no

¹ Communicated by permission of the Director of H.M. Geological Survey.

other mineral than this has been found developed in a true shale by this pneumatolytic action. In impure calcareous rocks, similarly altered, tourmaline is very rare, though if a band of interbedded shale occur, this mineral is not uncommon in it. In these calcareous rocks other special minerals have been produced by this gas-action, not only in great quantity, but also in considerable variety of species, and it is to these that attention is drawn in the first part of this paper.

Impure calcareous rocks occur in the neighbourhood of the granites in many localities and at several geological horizons; sometimes they show practically little but normal 'contact alteration' (thermo-metamorphism), in other cases the special effects of gas-action (pneumatolysis) are specially well marked. The calc-flintas, or impure banded calcareous rocks of the Meadfoot series of the Lower Devonian, have been selected as showing pneumatolysis and little 'contact-action' along their outcrop on the north side of the St. Austell granite. Similar rocks in the Upper Devonian have been taken as an illustration of normal 'contact-action' accompanied by a minimum of 'pneumatolitic action'; these latter rocks occur on the north side of the Bodmin Moor granite, in the Camelford area.

Bodmin area.

The calc-flintas of the Meadfoot series were first met with in a quarry on the west bank of the stream, about a quarter of a mile west of the hamlet of Tregullan, which lies about a mile and a half south of Bodmin. From this quarry the calcareous rocks have been traced westward for some ten miles, and in the course of their outcrop, owing to their extreme hardness, they often rise like a great wall above the softer killas to the north. At intervals all along this outcrop axinite can be met with, developed along small cracks and fissures, and at three points it has been proved by quarrying to be specially abundant. In the quarry just referred to, near Tregullan, the calcareous rock lies next an altered greenstone, and near their junction the former contains abundant axinite.

Associated with this axinite is a green pyroxene of markedly prismatic habit, as well as garnet and other minerals not easily identified by the unaided eye. These minerals are rare in the adjacent greenstone, the minute cracks in this being for the most part filled with small needles of actinolite, which if analysed would probably prove to contain a certain amount of some special gaseous element.

The second locality is an old quarry to the north-west of Lanivet,

and, though this quarry has long since been abandoned, some large loose blocks suggest that these minerals may be here more abundant than at any other point along the outcrop.

The third locality is in the steep banks of the stream near Tremore, some four miles south-west of Bodmin. Here two quarries have been opened for road-metal, one on each side of the stream; the first and largest belongs to the County Council, and from its height and size it gives a fine section of the rocks. The second, on the west side of the stream, though smaller, is the more interesting, as it is in this that blocks mainly composed of axinite have been obtained that at times weigh several hundredweight.

The dominant component of the sedimentary material here present is a hard flinty or horny rock, which occurs in thin bands of incessantly varying tint, though generally pale-coloured. The tint varies from white to pale yellow, buff, pinkish, and occasionally pale green; the texture varies from flinty, or horny, to very finely granular. The dominant type is essentially an admixture of very fine siliceous material with a varying percentage of lime (a calcareous sand), and the changes of tint and texture are essentially due to the varying proportion between the two components. Scattered through the whole mass are partings of brittle killas in which the siliceous mud contained no lime. This latter material, beyond being hardened, shows no sign of 'contact-action' by the granite; but the calcareous rocks do, certain lime-silicates occurring in the body of the rocks that are clearly due to contact-action. There is little sign of gas-action in the interbedded killas, but in a few cases this has proved to contain a great number of minute crystals of tourmaline.

The dip of the calcareous bands being very high, the beds have in many cases been forced open parallel to the stratification, and along the fissures thus formed the axinite and other minerals have been abundantly developed, of which a list and description are given later. This gas-action is here not confined to the calcareous rocks; for these are traversed by an elvan within which a considerable amount of bluish fluor-spar has been developed. Finally, a copper-lode occurs on the south edge of the larger quarry, and in the refuse of an old pit sunk in it, fluor-spar may be obtained in considerable quantity, while a peculiar form of chlorite is specially abundant.

Camelford area.

The impure calcareous bands in the Upper Devonian have a fairly extensive outcrop on the north side of the Bodmin Moor granite in the

Camelford area. These rocks have a more complex composition than those last described, and a greater diversity of minerals has been produced by the 'contact-action' of the granite. The minerals so produced can be studied in two quarries close to a small stream about a mile east-north-east of Camelford. The rocks in these quarries are also traversed by cracks and joints, within which certain minerals have been developed in such a manner as to suggest that they are of pneumatolitic origin; but Mr. Thomas's examination has shown that they are characteristic of thermo-metamorphism. The fact that the cracks were partly filled with calcite seems to have afforded special facilities for the development of crystallized minerals. When, later, the calcite was dissolved, the crystals, in particular those of idocrase, were left partially isolated, in a manner simulating the mode of occurrence of the axinite in the rocks previously described.

The minerals produced by gas-action and not developed by ordinary thermo-metamorphism are as follows:—

1. Axinite.
2. Prismatic, green pyroxene.
3. Fluor-spar.
4. Tourmaline.
5. Zinc-blende.
6. Bright-yellow garnet.
7. Talc, as found in the veins (the 'green peach' of the tin-miners).

Those developed by normal thermo-metamorphism are:—

1. Idocrase.
2. Garnet.
3. Pale and pale-green pyroxene.
4. Epidote.
5. Actinolite.

The last two minerals also occur associated with axinite in such a manner as to suggest that they may contain a small amount of some special element, such as boron, fluorine, &c. Their optical properties remain, however, the same as those of the normal types. It is hoped to isolate and analyse the actinolite and epidote from the pneumatolytic veins, to ascertain if such elements are present.

We will now pass on to a description, by Mr. Thomas, of the various mineral species which have been met with at the three localities mentioned above.

Tregullan quarry, Bodmin.

The most interesting specimens consist of an aggregate of badly-formed axinite crystals, patches of greenish pyroxene, actinolite, and epidote, with masses of crystallized calcite surrounded by, and including, a pale-yellow garnet.

The *axinite* builds crystals up to $\frac{1}{4}$ inch in greatest dimension, and of a dark brownish-purple colour; it seldom shows good outline except when it projects into patches of calcite or quartz, for in the body of the rock the crystals interfere with each other. When well formed it has a habit almost identical with those crystals from Tremore quarry, but, unlike most of the axinite from that locality, is not quite so tabular parallel to the face $r \{1\bar{1}1\}$.

The *pyroxene* is a monoclinic variety referable to *hedenbergite*. It occurs in minute crystals of marked prismatic habit, elongated parallel to the edge ab . The crystals are bounded by well-developed $a \{100\}$ and $b \{010\}$ faces modified by narrow prism-planes $m \{110\}$; they give rectangular cross-sections with feebly truncated corners and diagonal cleavage-traces. They are terminated by somewhat indefinite planes, probably referable to $c \{001\}$ and $u \{111\}$.

The maximum extinction in the prism-zone is approximately 42° , and the birefringence 0.023. In general characters it seems to agree fairly well with the pyroxene obtained by Mr. D. A. MacAlister and described by Dr. J. S. Flett¹ from the axinite-bearing rocks of Crugoes near St. Columb Major, but is practically identical in habit, optical properties, and associations, with that mentioned by Professor K. Busz² from certain limestones altered by the Dartmoor granite-mass. As pointed out by him it is one of the earliest calc-silicates to form, for it penetrates the garnet, axinite, and calcite with which it is associated.

The *garnets* are all pale coloured varieties, and range in colour from bright wine-yellow or canary-yellow to brownish-green.

The bright yellow garnets occur in minute rhombic-dodecahedra and seldom reach more than a millimetre in diameter. They have exceedingly bright faces of the form $\{110\}$ and no modification of this form could be detected. The crystals surround, and occur in, patches of recrystallized calcite from which presumably they have been formed, and the calcite surrounding many included garnets is optically continuous. Under the microscope the garnet crystals are seen to be strongly zoned,

¹ Geology of Newquay (sheet 346). Mem. Geol. Surv., 1906, p. 27.

² K. Busz, Neues Jahrb. Min., 1899, Beil.-Bd. xiii, p. 128.

each zone varying somewhat in colour and also in birefringence, for it is a characteristic of these garnets when free from large inclusions to be anisotropic.

The birefringence of certain parts of the outer zones is often as high as that of axinite, for which $\gamma - \alpha = 0.009$, but the central part is most often isotropic or nearly so. Sections through the centre at right angles to a trigonal axis show six distinct triangular sectors, the base of each triangle being the trace of a dodecahedral face, and its sides the traces of dyad axes. The birefringent layers are arranged parallel to the trace of the dodecahedron, and have their smaller axes of elasticity approximately parallel to the same line. These layers are differently orientated in adjoining triangles and present an orientation suggesting a rotation of 180° about a dyad axis. Extinctions range up to $+15^\circ$ with the trace of the dodecahedron in one triangle, and -15° in the two adjacent.

The small crystals are usually free from inclusions, but some of the larger are composed of a variety of minerals cemented together by small patches of bright yellow, isotropic garnet. These are bounded by the usual dodecahedral faces, but it is calculated that the included material often makes at least half their bulk. The included minerals are axinite, quartz, fluor-spar, actinolite, and pyroxene, showing that the garnets were probably one of the last metamorphic minerals to form.

A pale coloured yellowish-green garnet has also been met with in crystalline aggregates. The individuals consist of well-formed dodecahedra of the form $\{110\}$. They are fairly rich in manganese, and have strong anomalous double refraction, but are probably less mangani-ferous than those associated with idocrase at Tyland quarry, Camelford.

In composition the bright yellow garnet¹ seems to be related to the andradites, while the darker coloured varieties are intermediate between grossular and spessartine.

A bright yellow garnet similar to that of Tregullan has been known from Cornwall for some time, but so far as we are aware not described. As long ago as 1822 J. Carne² mentioned the occurrence of this mineral in association with axinite and other species in the Ros-common cliff near St. Just, and he also records the fact that it is

¹ A qualitative analysis of the garnetiferous portion of the Tregullan calciflints showed the presence of the rare earths, but it was found impossible to prove to which mineral they belonged. It was at first thought that they might be present in the epidote in the form of orthite, but it is quite likely that they may be contained in the bright yellow garnet.

² J. Carne, Proc. Geol. Soc. Cornwall, 1822, vol. ii, p. 309.

embedded in calcite near Lewellin. The deeper coloured varieties, which are generally more common, have been described by Busz¹ and Solly.²

Tourmaline is extremely rare in the more calcareous metamorphosed rocks, but a few minute, deep brownish-black needles have been noticed in one specimen. It is associated in this instance with the axinite, and yellow garnet and arranged in radiating groups of fine needles.

Actinolite. A microscopic, bright green variety with moderately strong pleochroism occurs in long prisms, usually enclosed in some other mineral (p. 120).

Haematite has been met with in minute plates and larger crystalline masses in the axinite-pyroxene-rock of Tregullan. It has the usual black metallic lustre, red streak, and is blood-red by transmitted light in thin sections. From its mode of occurrence it appears to occupy what were originally cavities in the rock, and it probably results from the metamorphosis of some ferrous compound, such as the carbonate, which most likely existed in the original calcareous deposit.

Zinc-blende is associated with the calcite patches in small quantity. It is brown in colour, has no definite outline, but shows the cleavages distinctly. A little iron-pyrites and fluor-spar are also present.

Epidote, in prisms and acicular forms, occurs in some quantity intimately associated with the pyroxene described above; it is similar in every respect to that met with at Tyland quarry.

Tremore, Bodmin.

The rocks of this locality which yield the best specimens were evidently more calcareous than those of Tregullan, for such minerals as the pyroxene and epidote are much less abundant. The calc-flintas in the larger Tremore quarry are cut by a copper-vein which has yielded a few minerals not recognized in the calc-flintas themselves.

Axinite. The axinite-rock of this locality consists chiefly of aggregates of small crystals loosely cemented by quartz and calcite. The mineral builds small, blade-like crystals of pale-plum to cinnamon-brown colour with deeply striated faces. A few crystals which were measured gave the following angles and forms:—

¹ K. Busz, loc. cit., 1899, p. 125.

² R. H. Solly, Min. Mag., 1886, vol. vi, p. 202.

	Measured.	Calculated.
$Mr = (1\bar{1}0):(1\bar{1}1)$	$45^{\circ} 15'$	$45^{\circ} 15'$
$rm = (1\bar{1}1):(110)$	$64^{\circ} 23'$	$64^{\circ} 22'$
$Ms = (1\bar{1}0):(201)$	$33^{\circ} 24'$	$33^{\circ} 18'$
$Mx = (1\bar{1}0):(111)$	$49^{\circ} 4'$	$49^{\circ} 25'$
$My = (1\bar{1}0):(021)$	$79^{\circ} 25'$	$79^{\circ} 12'$

The most common forms are $M\{1\bar{1}0\}$, $r\{1\bar{1}1\}$, and $m\{110\}$. The form $r\{1\bar{1}1\}$ is developed at the expense of the others and is deeply striated parallel to the edge $(1\bar{1}1)(1\bar{1}0)$. The crystals are tabular parallel to the form $r\{1\bar{1}1\}$. Crystals of slightly deeper colour and thicker build have been met with which have the forms $M\{1\bar{1}0\}$, $s\{201\}$, $x\{111\}$, and $y\{021\}$ more or less equally developed. The form $e\{1\bar{1}1\}$ is also present on some of these crystals.

Extinctions on $r(1\bar{1}1)$ measured to the edge rM give $8\frac{1}{2}^{\circ}$; and the pleochroism is pale-plum parallel to the edge rM and colourless to a faint shade of yellow at right angles. This pleochroism, although fairly strong, is not so intense as that shown by axinites from the uranium mine at Grampound Road and several other Cornish localities.

Amphibole. Many of the best axinite crystals occur embedded in a pale green silky *asbestos*, a mineral often found in association with axinite-rocks, as described¹ from other localities in Cornwall, Devonshire, and the United States.

In the axinite-rock, especially in the more massive varieties, patches of a green, vitreous mineral were noticed running up to about three-quarters of an inch in diameter and pierced by axinite crystals. Under the microscope this vitreous mineral proved to be quartz which was penetrated by numberless extremely slender crystals of a pale green actinolite, which gives the colour to the whole mass. The pleochroism of the amphibole is slight, and the extinction $\epsilon_{\lambda}c = 18^{\circ}$ approximately. The maximum absorption is parallel to c , and the zone of elongation has a positive sign. Similar needles are enclosed in crystallized calcite to which also they impart the same green colour.

The most interesting amphibole is that which occurs in the drusy cavities of the axinite-rock; it consists of minute, extremely slender needles of a dark brown to black colour, forming a woolly mass and recalling strongly the breislakite² of Vesuvius and the Capo di Bove near Rome.

¹ R. H. Solly, loc. cit., 1886, pp. 210-211.

² E. Weinschenk, Zeits. Kryst. Min., 1903, vol. xxxvii, p. 442.

In view of Weinschenk's description of this species, however, the resemblance between it and the mineral from the axinite-rock is only superficial. The individual needles, which have a submetallic lustre, reach two centimetres in length. They are striated parallel to the long axis and are bounded by the faces $m\{110\}$ without any recognizable terminations. The zone of elongation has a positive sign, and the extinction $c\wedge c' = 18^\circ$ approximately. The maximum absorption in the prism-zone is for light vibrating parallel to c , which is yellowish-green, and at right angles to c yellowish.

The deep colour of these needles when viewed by reflected light is due to bunches of black oxide of manganese deposited upon them, but when treated with dilute hydrochloric acid they appear pale green and are then indistinguishable from actinolite. In this state they resemble the byssolite of Traversella. There is no doubt that the brown woolly amphibole occurring in the druses of the axinite-rock was originally contained by some other mineral, probably calcite or quartz; and fragments of the actinolite-bearing calcite mentioned above when treated with dilute hydrochloric acid yielded aggregates which differed from it only in the absence of the clusters of manganese oxide. It is, therefore, probable that these woolly aggregates owe their present characters to the solution of the calcite or quartz in which they were originally embedded and the deposition of manganese oxide on the freed needles.

The other minerals met with at Tremore, including yellow garnet and pyroxene, are identical with those already described from Tregullan; but from the copper-vein in the large quarry we recognize a deep purple fluor-spar, well-crystallized talc, zinc-blende, and masses of chlorite in the form of 'peach'. The copper-ore is massive chalcopyrite. The talc has a well-marked cleavage; the cleavage-fragments show the emergence of a negative bisectrix normal to the flake and an axial angle of 10° – 20° in air.

Tyland quarry, Camelford.

The minerals from this locality belong almost exclusively to those usually regarded as due to true contact-metamorphism, but at the same time small quantities of axinite, fluor-spar, and allied minerals of pneumatolytic character are present.

Garnet. The garnet of Tyland quarry occurs massive in the more calcareous bands of the calc-flintas and well crystallized on certain joint-faces. It has a cinnamon-brown to brownish-yellow colour, and occurs with idocrase and quartz. The form is that of the simple rhombic-

dodecahedron $\{110\}$ modified by very narrow planes of $\{211\}$. The faces $\{110\}$ are deeply striated parallel to their shorter diagonal.

These garnets are often hollow and are built up around other minerals. A qualitative analysis showed the presence of calcium, iron, manganese, a little magnesium, and no chromium, indicating that the mineral should probably be referred to the grossulars or spessartines. Optically, these garnets are strongly birefringent, the double-refracting layers being arranged in a similar manner to those of the yellow garnet described from Tregullan.

Idocrase occurs in colourless to pale yellowish-green or yellowish-brown prisms, deeply striated parallel to the vertical axis, and usually terminated by the basal plane alone. The prisms are rectangular, being bounded by the form $m\{110\}$; no modifications in this zone were noticed, but very narrow pyramids, probably $p\{111\}$, were observed to truncate the edge between the prism and the basal plane. Modifications of the quoins occasionally occur. The crystals average three to five millimetres in length and are seldom more than one millimetre in width. Occasionally, however, they reach a centimetre in length. In some instances they have been noticed implanted on the garnets described above, after the manner of those of Péguyères in the Pyrenees.¹

Optically, they show the usual low birefringence in the prism-zone, and cross-sections show a bisectrix. The mineral is most often biaxial with an angle between the axes in air varying from 0° to 10° .

This mineral is one of the best known products resulting from the metamorphism of calcareous rocks, but so far as we are aware has not previously been recorded from Cornwall.

Epidote. Well-crystallized epidote occurs associated with the garnet-idocrase-masses both in the rock and on the joint-faces. On the joints it builds extremely long (up to 4 cm.) prismatic crystals, elongated parallel to the axis of symmetry, of a pale greenish-brown to greenish-purple colour. They are bounded by the $a\{100\}$ and $c\{001\}$ faces, giving generally rhombic cross-sections, whilst occasionally hexagonal cross-sections may be observed, due to the presence of $r\{10\bar{1}\}$ in addition. Light vibrating parallel to b is plum-coloured and at right angles to this yellowish-green. This pleochroism, together with the other optical properties, suggests an epidote with a percentage of ferric oxide of about 7 to 8, somewhat similar to the epidote from Inverness-shire, but slightly richer in iron. The pleochroism is, however, almost identical with that of the Inverness-shire mineral.²

¹ A. Lacroix, 'Minéralogie de la France.' 1893, vol. i, p. 163.

² H. H. Thomas, *Min. Mag.*, 1906, vol. xiv, p. 112.

Chlorite. A chlorite of a dark green colour occurs well-crystallized in association with the garnets, &c. It has a perfect cleavage parallel to the base and shows the emergence of a negative bisectrix normal to the flakes. The angle between the optic axes is extremely small, and occasionally the mineral seems to be uniaxial. It is probably related to the penninites.

In the less calcareous bands a pyroxene occurs and is apparently similar to that already described. Axinite with the usual characters occurs in small quantities, but in this case seems to be moulded on the garnet.

Supplementary notes on the mineral Kaolinite.

By ALLAN B. DICK.

[Communicated by Professor Miers, and read March 17, 1908.]

IN the year 1888 I gave before the Mineralogical Society an account of the forms and optical characters of some minute crystals of kaolinite from Anglesey.¹ At that time I was unable to ascertain whether the mineral was optically positive or negative, and it was stated that the axial angle $2V$ would approximate to 90° . Subsequently, by the aid of oil-immersion lenses and condensers of high angular aperture (numerical aperture = 1.25), it was found that the mineral is optically positive and that the acute bisectrix is normal to the clinopinacoid (the obtuse negative bisectrix emerging through the basal plane). The optic axial angle in air was determined with an eye-piece micrometer to be $2E = 121^\circ$, with a possible error of one or two degrees, due to the small size of the crystals and the consequent weak interference-figures.

The mean refractive index, which was previously stated to be about the same as that of Canada-balsam, is in reality somewhat higher, being 1.563 for sodium-light. This value was determined by the Becke method in a mixture of oils, the refractive index of the oil being found on the total reflectometer. No difference could be observed in the refractive index when the crystals were viewed through the basal plane and through the clinopinacoid. Calculated from this refractive index and from $2E = 121^\circ$, the value for $2V$ is about 68° , instead of near 90° .

It is to correct these errors that the present communication is made. It was also stated that the angle of extinction on the plane of symmetry relative to the trace of the basal plane had a maximum value of 20° . This observation is, however, not very reliable, owing to low double refraction and to the dispersion. But until thicker crystals are available for study this must remain, although it would have been better to have said that the extinction-angle lies somewhere between 15° and 20° .

¹ A. B. Dick, 'On kaolinite.' *Min. Mag.*, 1888, vol. viii, pp. 15-27, plate III. Compare H. A. Miers, *Min. Mag.*, 1890, vol. ix, p. 4.

The strength of the double-refraction, which was previously stated to be rather less than that of quartz, has been determined afresh by means of a mica-wedge. This wedge was constructed in the following manner. A sheet of muscovite with a uniform thickness of approximately 0.02 mm. was cut into strips along lines parallel to the trace of the optic axial plane, and of suitable width to pass through the eye-piece of the microscope. These strips were then laid one upon another, each strip being a little shorter than the one beneath it; and the pile of strips was mounted in Canada-balsam between two thin plates of glass. There were nine of these strips, and each one of them was large enough to fill the field of vision. The wedge had thus an increasing thickness, step by step, from about 0.02 to about 0.18 mm. The first step produced a retardation of one-sixth of an undulation of sodium-light, and at the thicker end of the wedge the retardation was one-and-a-half undulations. Examined in convergent polarized sodium-light, the sixth step gave an interference-figure showing the first ring around each optic axis meeting in the centre of the field and remaining dark during the entire rotation of the nicols. This step also remained dark in parallel polarized sodium-light during an entire rotation, as though the mineral were isotropic; thus showing that the wedge was accurately constructed.

A microscope-slide was strewn with the larger of the kaolin crystals from Anglesey. Crystals resting on the basal plane and of uniform thickness were examined between crossed nicols by crossing them at 45° with the mica-wedge. One crystal was found which gave compensation with the second step of the wedge. It was picked out on a waxed needle, which could be turned in the focus of the microscope, and its thickness measured by comparison with a stage-micrometer ruled to $\frac{1}{10}$ and $\frac{1}{100}$ mm. The thickness of the crystal was 0.05 mm., that of the muscovite being 0.04. The double-refraction of kaolinite on the basal plane is therefore one-fifth lower than that of the muscovite of which the wedge was made.

The slide was then searched for a crystal resting on the clinopinacoid, like crystal No. 3 figured in the previous paper. None was found thick enough to compensate the second step of the wedge, as did the crystal resting on the basal plane. Accordingly, one was selected which compensated the first step of the wedge. It was picked out as before and measured. Its thickness was found to be 0.063 mm., that of the muscovite being 0.02 mm. The strength of the double-refraction on the plane of symmetry is therefore rather less than half of that on the basal plane.

The same crystal was then turned on its edge so as to look along a direction perpendicular to the orthopinacoid. When set at 45° to the crossed nicols it showed at its thickest end (the base of the crystal) the bluish-green colour of the second order, and was compensated by the eighth step of the wedge. The thickness of the crystal at this part was 0.20 mm., so that the double-refraction in this direction has about the same strength as on the basal plane. It must, however, be remarked that this observation is less accurate than those made on the basal plane and the clinopinacoid, on account of the wedge-shaped form of the crystal and the absence of the orthopinacoid.

The strength of the double-refraction ($\gamma - \beta$) on the cleavage-surface of the muscovite employed in making the wedge was determined by a comparison with the colour-diagram of birefringences given by Michel Lévy and Lacroix.¹ The sixth step of the wedge, with a thickness of 0.12 mm., gives the deep indigo-blue adjacent to the first sensitive tint, corresponding to a birefringence of 0.005 in the diagram.

The birefringences of the Anglesey kaolinite are therefore approximately:—

$$\text{On the basal plane, } \gamma - \beta = \frac{0.04 \times 0.005}{0.05} = 0.004,$$

$$\text{On the plane of symmetry, } \beta - \alpha = \frac{0.02 \times 0.005}{0.063} = 0.002 \text{ nearly.}$$

Well-crystallized kaolinite appears to be of rather rare occurrence. The crystals which I have previously described, and on which the determinations given above have been made, are from the neighbourhood of Amlwch in Anglesey. Mention may therefore be made in this place of the following additional British occurrences.

In the year 1895 Mr. R. H. Tiddeman met with a cream-coloured powder filling small veins in the limestone of Hambleton quarry, near Bolton Abbey in the West Riding of Yorkshire. This I examined at the time and found to be kaolinite. It is slightly stained by iron oxide, but becomes white on digestion in hydrochloric acid. The crystals are as perfect as those from Anglesey, but they are about a fourth smaller, and on none of them are the clinopinacoidal faces largely developed. In a letter written at the time Mr. Tiddeman said: 'Briefly, it occurs in veins running through about six feet of limestone lying at high angles, 60° or 70° , between two partings of shale. The surface of the shale seems also to be lined with it. The whole mass of the rock is much contorted.'

¹ A. Michel Lévy and A. Lacroix, 'Les Minéraux des Roches.' 1888.

Another occurrence of the mineral was observed at about the same time by Mr. W. M. Hutchings in the sandstone of a coal mine near Newcastle-on-Tyne. It was there found as a loose, snow-white powder, filling, to the thickness of some inches, a crack or parting in connexion with a small vein of lead-ore. The crystals are all very minute; they have a hexagonal outline, and none are specially developed in the direction of the clinopinacoid.

A third occurrence is in the millstone grit of a quarry at Congleton in Cheshire. Here the mineral fills the spaces between the grains of grit, and forms a loose aggregate of very small, white scales, some of which show perfect hexagonal outlines, whilst others are grouped in chlorite-like forms.

The statement in the textbooks that kaolinite is optically negative would appear to have originated from the examination made by A. Des Cloizeaux¹ of the varieties pholerite and nacrite, he having observed through the basal cleavages a wide-angled, negative bisectrix. I have been unable to obtain a specimen of pholerite for examination, and have met with only two of nacrite, both of which are probably from the Einigkeit mine near Freiberg in Saxony. These consist of fan-shaped aggregates of pearly scales, which have the same chemical composition,² hardness, specific gravity, and refractive index as the Anglesey kaolinite; but they differ from this in being optically negative with the acute bisectrix practically normal³ to the cleavage and $2E = 103^\circ$ approximately (hence $2V = 60^\circ$). Through the basal cleavage of the Anglesey crystals only a diffuse negative bisectrix with the axes far outside the field is to be observed. The same is also the case with the other British kaolinites mentioned above, and with that described in 1887 by H. Reusch from the National Bell mine, Colorado, which I have had an opportunity of examining.

It must, therefore, be concluded that there are two varieties of kaolinite, one optically positive and the other optically negative; the former being the more common and better crystallized type.

¹ A. Des Cloizeaux, 'Manuel de Minéralogie.' 1862, vol. i, pp. 190, 549.

² An analysis made on a very small amount of material gave: SiO_2 , 47.1; Al_2O_3 , 39.1; H_2O , 14.0 = 100.2.

³ The cleavage flakes usually show a division into three sectors; in the central one the emergence of the negative bisectrix is normal, whilst in the adjacent sectors it is inclined slightly away from the centre on either side.

Kaolinization and other changes in West of England rocks.

By FRANCIS H. BUTLER, M.A., A.R.S.M., L.S.A. (Lond.).

[Read June 16, 1908.]

THE behaviour of a mass of molten but cooling igneous rock under moderate pressure may be compared to that of liquid cupelled silver, which at a certain temperature can no longer retain the oxygen, many times its volume, that it has occluded. Thus, during the submarine eruption off the island of Pantelleria in 1891, blocks of lava that swam for a while on the surface of the sea exploded with violence. Chilling by contact with sea-water had occasioned exactly what Lowthian Bell¹ observed to happen on the sudden cooling of masses of slag by contact with water. There was a discharge within the set outer envelope, at something near a red heat, of previously dissolved water and gases, converting the floating ejectamenta into a species of bombs.

The sight of Vesuvius quiescent, but day after day under its pear-shaped cloud of vapour, helps one to form some conception of what must be the bulk of the emanations of a mass of cooling granite. These undoubtedly are chiefly water, but water the heat of which, not being dissipated in volcanic disturbances, is exercised in the promotion, under pressure of superincumbent strata, of chemical changes both in the partly consolidated outer crust of the granite and in the contact-region.

In the first volume of this Magazine H. C. Sorby remarks of rocks that are molten but are under great pressure—such, in fact, as were the West of England granites—that they probably contain water dissolved either physically as a gas in a liquid or chemically as it is in a hydrate, i.e. the water does not dissolve the rocks, but the rocks the water.² As the rocks cool, highly compressed steam remains more or less disseminated in them until the temperature reaches the critical

¹ L. Bell, Journ. Iron and Steel Inst., 1881, pp. 534 and 540.

² H. C. Sorby, Quart. Journ. Geol. Soc., 1858, vol. xiv, p. 489.

point, when the solvent action of greatly expanded liquid water comes into play.

Examination of the outermost exposures of granites in the West of England and of their offsets, or dikes, affords proof of the operation of agencies that scarcely affected the main mass. It would appear that, owing either to changes in the density of the consolidating exterior¹ or, more probably, to convection-currents dependent upon differences rather in vascularity than in temperature,² there was a perpetual descent of fragments of solid or streams of more or less fluid rock from the uppermost portions of the magma. These, previous to their descent, discharged their gaseous and vaporous contents into the cooled exterior and the strata in contact therewith. The first results of the action of this discharge (pneumatolysis) upon the outlying portions of the granite were usually increased vesicularity in the quartz and assumption by much of it of the idiomorphic condition, also the formation of tourmaline, commonly brown or yellow, but sometimes blue in parts. Further action is evidenced by the bleaching or destruction of biotite and muscovite, and their replacement by tourmaline or, as in some elvans, by chlorite and rutile, and alteration of feldspars, these last being rendered turbid by the production of fluid cavities and some degree of kaolinization, especially in their inclusions of what Dr. J. S. Flett³ has shown to be oligoclase-albite. Further changes in the feldspar result in the production of secondary silica,⁴ muscovite, topaz, and probably also andalusite. In the china-clay districts kaolinization is a marked feature. This and further effects of pneumatolysis will be considered later.

The period during which pneumatolytic processes affected the rocks of Cornwall and Devon may have been long protracted, even geologically speaking. It took ten centuries of puy action to effect the softening that led to the sudden shattering of the Kobandi peak of Bandaisan, Japan,⁵ and in the West of England both granite and killas can be shown to have undergone more than one series of changes.

To attempt to discuss the source of the water that permeated the West of England rocks at the time of and subsequent to their intrusion would be to go beyond the scope of the present paper. The behaviour

¹ C. E. Dutton, *Amer. Journ. Sci.*, 1883, vol. xxv, pp. 220-221.

² O. Fisher, 'Physics of the Earth's Crust.' 2nd edit., 1889, pp. 47 and 51.

³ J. S. Flett, *Mem. Geol. Surv., Land's End District*, 1907, p. 50.

⁴ S. Allport, *Quart. Journ. Geol. Soc.*, 1876, vol. xxxii, p. 413.

⁵ Michie Smith, *Proc. R. Soc. Edinburgh*, 1889-90, vol. xvii, p. 65.

of molten slags as solvents of gaseous bodies¹ affords reason for considering that the vapour of water as such or its dissociated elements² are directly absorbed by liquid lava. Angelot³ conceives it to be quite possible for a column of water communicating with the surface of the globe to exert sufficient pressure to keep its base in the liquid condition when actually in contact with molten rock. That meteoric or oceanic water is occluded by the magmas of igneous rocks is, however, regarded as far from proven.⁴ Messrs. Chamberlin and Salisbury⁵ close their summary of the theories on this subject with the remark that the balance of present evidence seems to favour the view that the steam and other gases of igneous rocks come with them from their source deep in the earth. Hence one might, perhaps, be allowed the deduction that the magmas of the earth's lavas have for long been growing progressively anhydrous. Dr. H. J. Johnston-Lavis,⁶ on the other hand, states that there is reason to believe that in their deep-seated sources lavas contain little or no water, and he maintains that when igneous matter is intruded into porous, water-bearing strata a process of dialysis goes on between the colloidal magma and the water in the strata.

Vesicles in quartz containing liquid and commonly a bubble, often abundant in granite, are especially so in its pneumatolysed derivatives, and perhaps most in schorl-rock. Fifty years ago H. C. Sorby⁷ noted the occurrence of cubic crystals of salt and of minute prisms, presumably of selenite, in the quartz replacements of large felspar crystals in portions of the granite at Trevalgan, near St. Ives, Cornwall. His deductions from a study of the contents of the vesicles of quartz were questioned by S. Allport⁸ on the ground that these contents were variable. This objection, however, loses force when one perceives that the differences in contents were determined by the act of crystallization of the quartz, which distributed from within outwards along lines of fracture (usually with a well-marked conchoidal curve, but frequently

¹ A blast-furnace slag from Trignac, Allier, France, in the British Museum (Natural History) collection yields hydrogen sulphide as readily as fetid barytes when scratched.

² L. Bell, *loc. cit.*, p. 541.

³ V. F. Angelot, *Bull. Soc. Géol. France*, 1842, sér. 1, vol. xiii, pp. 188-189.

⁴ J. F. Kemp, in 'The Genesis of Ore-Deposits,' published by the Amer. Inst. Mining Eng., 2nd edit., 1902, pp. 687-688.

⁵ T. C. Chamberlin and R. D. Salisbury, 'Geology,' 1904, vol. i, p. 607.

⁶ H. J. Johnston-Lavis, *Quart. Journ. Geol. Soc.*, 1885, vol. xli, *Proc.*, p. 104.

⁷ H. C. Sorby, *Quart. Journ. Geol. Soc.*, 1858, vol. xiv, p. 475.

⁸ S. Allport, *Quart. Journ. Geol. Soc.*, 1876, vol. xxxii, p. 408.

obliterated owing to residual plasticity in the silica) the constituents of a cooling gaseous liquid. Some of the little clefts received crystals with liquid and portions of any gas present, and others liquid only. Differences in the size of vesicles in quartz, due partly to irregular scattering of contents during its crystallization, may be ascribed mainly to the varied hydration of magmas. The quartz of a muscovite-tourmaline-granite, with kaolinized feldspars, from St. Michael's Mount, is grey with a multitude of minute vesicles, each with its bubble, the mobility of the uncrystallized silica having been insufficient to permit the coalescence of disseminated liquid. In the junction-rock between granite and killas at Trewavas Head, Cornwall, and in the schorl-rock of Baleswidden the vesicles are large. Vesicles, somewhat masked by radiating needles of schorl, are present in the quartz of both luxulyanite and trowlesworthite (fig. 1A),¹ cavities in a microscopic preparation of the latter showing well-defined salt crystals. Salt crystals (sodium or potassium chloride) are well seen in the quartz-vesicles of the tourmaline-granite of Moor House quarry, Shipley, Devon, of the Leather Tor schorl-rock, the Stenna Gwynn gilbertite-quartz-rock, the china-stone from near Trethosa, Cornwall, and many other West of England derivatives of granite.

An explanation of the development of idiomorphic quartz in the outer zone of granite masses and in their apophyses, the elvans of Cornwall and Devon, is furnished by a consideration of the condition of those rocks previous to their final consolidation. 'We must never forget,' remarks Professor J. W. Judd,² 'that in the deep-seated rocks . . . the whole mass, crystals and base alike, must be permeated by liquids and gases; and chemical reactions . . . can readily take place.' This is especially true of the region of pneumatolytic change. In this, among the mineralizing agents continually received from the magma, because less soluble therein than in water, or rejected therefrom during crystallization, there are present, to use the words of Arrhenius,³ the ions of carbonic and boric acids and hydrogen sulphide, the hydrates of which are highly soluble in water without being dissociated. Silicic acid also is taken up by the water, which not only exercises the remarkable solvent powers it possesses at high temperatures, but facilitates molecular movement by promoting the fluidity of the mass affected.

¹ Seemingly not detectible in the first microscopic preparation. (See T. G. Bonney, *Trans. R. Geol. Soc. Cornwall*, 1883, vol. x, pp. 180-186.)

² J. W. Judd, *Quart. Journ. Geol. Soc.*, 1889, vol. xlv, p. 181.

³ S. Arrhenius, in 'The Genesis of Ore-Deposits,' *sup. cit.*, p. 644.

The very general absence of mica from the elvan dikes of the West of England can scarcely be attributed in the majority of instances to the existence of contraction-fissures affording easy passage into them of solvents from below or of surface-water from above and laterally, for the presence in them of idiomorphic quartz is another frequent characteristic. Moreover, the existence of abundant fine muscovite in the groundmass of elvans, as Dr. J. S. Flett remarks,¹ is probably a certain indication of pneumatolytic action, for muscovite is very rarely a primary ingredient of these rocks. This mica, evidently a dekaolinitization product, is well seen in the pneumatolysed solid overburden in the Higher Nine Stones clay-pit, St. Austell, a rock exhibiting, with very little primary tourmaline, large, only superficially blanched Carlsbad-twins of orthoclase, and numerous, slightly eroded bipyramids of quartz. Idiomorphic quartz may be met with in those portions of many granitic masses that from their external position may be considered to have undergone some degree of pneumatolytic action, as, for example, the tourmaline-granite of Moor House quarry, on the borders of Dartmoor, that forming the eastern buttress of Gunnislake quarry, and the pinitiferous granite of Kit Hill, Cornwall. We are constrained, therefore, to seek for an explanation of this characteristic in conditions common to both granite and elvan previous to their final consolidation.

In granite subjected to pneumatolysis after crystallization of its constituents the mineral most prone to suffer disintegration and solution would be biotite, and then would follow muscovite and the feldspars of the groundmass. Biotite, if not converted into tourmaline, which would require all but about 4.5 or 5 per cent. of its silica, would yield on decomposition some two-fifths of its weight of the latter substance. From muscovite a still greater amount would be obtained. The granules of original quartz in granite more or less liquefied by pneumatolytic action, unless completely dissolved, would serve as nuclei for the growth of idiomorphic crystals, the granules availing themselves of nascent silica derived from mica taken into solution. The removal of the bases of the mica, if effected by flow of the pneumatolysing fluid, would deprive any feldspar crystals that had escaped destruction—probably in most cases a goodly proportion—of the alumina and potash they required for fresh growth, and the resultant solid rock would contain an abnormal proportion of quartz to its feldspar and no mica. The assumption by the idiomorphic quartz of the bipyramidal prismless

¹ J. S. Flett, loc. cit.

shape would seem to be conditioned by the nature of the menstruum in which it grew. Whether it is a result of hydrostatic pressure is a question that could be determined only by ascertaining what is the variation with pressure of the molecular surface energy of the various faces of a quartz crystal. The growth of the quartz phenocrysts in dikes is evidently dependent on the temperature of the magma and its degree of liquidity—increased by relief of pressure, on the bulk of the extruded mass and the rate at which it loses heat to adjoining rocks, and on the demands for silica made by growing felspar. It is manifest that the variation in shape of the phenocrysts from bipyramids with slightly blunted edges to rounded blebs must be attributed to erosion subsequent to re-growth. It has been suggested¹ that this rounding may be caused by hydrofluoric acid; the results of chemical experimentation, however,² intimate that, in the presence of orthoclase, quartz would be little, if at all, affected by that acid. It seems safe, therefore, to conclude that erosion of the quartz phenocrysts of the West of England and similar elvans was effected by the magma in proportion as it was desilicified by the enlargement or re-formation of felspar crystals.

The common occurrence of tourmaline, usually a dark variety (schorl), at different stages in the metasomatism of granite, indicates the existence of a magma constantly impregnated with some compound of boron. In the Shipley granite, for example, already mentioned, the presence of schorl in fissures in fractured orthoclase demonstrates tourmalinization after considerable progress in consolidation. Sedgwick long ago³ remarked on the prevalence of schorl in the rocks usually associated with granite in Cornwall. These he groups as rocks composed of the constituents of granite with another mineral, commonly schorl or tin-stone; those with no mica, or with chlorite or, more commonly, schorl replacing it; and schorl-rock, i.e. quartz with schorl only. He remarks, too, that the last may have a scoriaceous appearance owing to the removal of original felspar.

In considering the question of the alteration of biotite to tourmaline, it is important to note that tourmaline is a compound unaffected by acids, and decomposable artificially, with liberation of water, only when its chemical individuality is completely destroyed by strongly heated

¹ J. H. Collins, 'The Hensbarrow Granite District.' 1878, p. 9.

² H. Rosenbusch, 'Microscopic Physiography of the Rock-making Minerals,' transl. J. P. Iddings, 4th edit., 1898, p. 108.

³ A. Sedgwick, Trans. Cambridge Phil. Soc., 1821, vol. i, pp. 105-106.

fused alkaline carbonate.¹ In biotite are present all the constituents, save titanium and boron, that Scharizer² has shown to be present in brown tourmaline, which may be found in West of England granites either associated with biotite or without it. The pneumatolysis of an igneous acid rock lacking in biotite or its constituents may result in the formation of such a compost as the topaziferous aplite that occurs in contact with killas at Meldon, Devon,³ containing, with white mica, tourmaline of a light greenish or, more rarely, of a pink tint. Most commonly, however, in the West of England the rock in which primary tourmaline came to be developed was a typical granite containing an appreciable quantity of biotite.⁴ In trowlesworthite manifestly some of the brown tourmaline is secondary, for crystals of it may be seen moulded on plagioclase. Without such evidence it may be hazardous to infer that the dark-coloured tourmaline in a micaless granite probably usurps the place of biotite. In Carn Grey quarry, St. Austell, the selvage of the granite section shows schorl replacing biotite as the ferro-magnesian mineral. The non-micaceous character of many schorlaceous elvans gives some support to the opinion that their micas have found a new existence in dark tourmaline. In rocks such as luxulyanite, trowlesworthite, and the schorl-rock of Single Rose clay-work, St. Austell, are distributed fair-sized tourmaline crystals of a yellow, orange, or brown colour, sometimes with patches of blue; and these were undoubtedly part of the groundmass of the parent-granite before it underwent kaolinization, and must in many cases be reconstituted biotite. In variability of tint and in presenting longitudinal and transverse cracks these crystals closely resemble the isolated tourmaline crystals to be found in most other borated West of England rocks. Additional features are outlines indicating that they have for the most part suffered irregular erosion before envelopment in acicular schorl of post-kaolinization date (fig. 2). In some instances a crack running through two distinct fragments may be seen to have become discontinuous owing to the intrusion between them of an isthmus of fine-grained quartz-schorl-rock. These fragments by their like optic orientation show that they are parts of one crystal. The same observation was made by Allport with respect to tourmaline in the metamorphic

¹ R. Scharizer, *Zeits. Kryst. Min.*, 1887, vol. xv, p. 343.

² R. Scharizer, *loc. cit.*, pp. 348-349.

³ J. J. H. Teall, 'British Petrography,' 1888, p. 316.

⁴ See T. G. Bonney, 'On the microscopic structure of trowlesworthite.' *Trans. R. Geol. Soc. Cornwall*, 1883, vol. x, pp. 180-186.

rocks surrounding the Land's End mass of granite.¹ The erosion of some of it possibly explains his conclusion that the quartz of certain of his specimens had impressed its form on the tourmaline, and must therefore have been the earlier to solidify. This, however, is perfectly true of late-formed crystals of brown tourmaline in the Cligga Head granite, some of them being protected on one side by quartz and there



Fig. 1.—A. Quartz with vesicles ;
in trowlesworthite.
B. Quartz on eroded and
altered felspar : Rose-
mellyn Farm, Cornwall.



Fig. 2.—Eroded tourmaline in
quartz-schorl envelope ; in
luxulyanite.

intact, and on the other side eroded. The schorl-rock of Leather Tor, Devon, shows fragmentary tourmaline filling in the interstices of a mosaic of quartz. Here the irregular outlines of the tourmaline must be due to both erosion and fracture, for some neighbouring fragments have the same optic orientation. There can be no doubt that the crystallization of the finely acicular schorl of the metasomatized rocks of the Hensbarrow granite district was in part contemporaneous with that of the quartz accompanying it. In a much kaolinized granite on Rosemellyn Farm, in the parish of Roche, Cornwall, quartz instead of schorl has in places crystallized on the eroded felspar crystals projecting into spaces vacated by the groundmass, and its free surfaces have then been capped by acicular schorl (fig. 1B). Luxulyanite, again, exhibits zoning of quartz crystals by dust-like microlites of schorl entangled among extruded liquid particles (fig. 3). In this rock and trowlesworthite the re-growth of the eroded single yellowish or brownish

¹ S. Allport, *Quart. Journ. Geol. Soc.*, 1876, vol. xxxii, p. 416.

tourmalines seems to have been arrested by the development of the acicular crystals or of a band of blue tourmaline.

It is clear that contact with acids cannot have occasioned the erosion of tourmaline observable in various West of England rocks. As we have seen, tourmaline, like topaz, is unaffected by acids. Its decomposability by melted alkaline carbonates suggests that its erosion may be due to exposure to the action of hot solutions of these salts, their effect being enhanced by the presence of carbonic acid and by pressure. A clue to the source of the alkaline carbonates is afforded by the existence of remnants of china-clay in greisen, schorl-rock, luxulyanite—in short, in West of England tourmalinized rocks generally, and the obvious inference is that the original felspar therein underwent kaolinization. It is evident that the erosion did not take place when a fresh supply of tourmaline, the acicular variety, was being added to the schorlaceous rocks. It is equally obvious that the eroded mineral did not suffer by the pneumatolysis during which it was evolved. If, as appears to be the case, the erosion took place during kaolinization, and the agent therein was a solution of carbonic acid, alkaline carbonates must have come into contact with the tourmaline, whether they were originally present in the solution or not, for their production would be a necessary consequence of the leaching of the alkaline silicates out of felspar and of their decomposition by carbonated water.

A further argument in favour of the theory that the kaolinizing agent was a solution of carbonic acid—possibly very weak, but at a high temperature—is afforded by china-stone. This rock has been defined by Mr. J. H. Collins¹ as intermediate in regard to decomposition between china-clay rock and hard granite. It is a granite that, though tourmaline may be absent from it, has lost, with some 60 per cent. of the potash of its felspar, the whole of its biotite; and what muscovite is present may, like the accompanying gilbertite, be regarded as a secondary, i. e. post-kaolinization product. As observed by Waldemar Lindgren,² biotite is unstable under the influence of solutions of carbon dioxide and alkaline carbonates, consequently the kaolinization during which the biotite and doubtless, after it, the original muscovite disappeared may have been the work of those agents. We have in addition the testimony of Prof. J. H. L. Vogt,³ who rejects the theory of Daubrée,

¹ J. H. Collins, 'The Hensbarrow Granite District,' 1878, p. 31.

² W. Lindgren, in 'The Genesis of Ore-Deposits,' op. cit., 1902, 2nd edit., p. 530.

³ J. H. L. Vogt, *ibid.*, pp. 661-668.

adopted by Mr. J. H. Collins,¹ that kaolinization is due to solutions of fluo-silicates or fluo-borates. Prof. Vogt takes the view that very weak carbonic acid water can remove lime, magnesia, and alkalis, and produce kaolin, whereas water rich in dissolved alkaline and earthy carbonates favours carbonatization and sericitization. He cites the kaolinization of a labradorite-rock at Ekersund-Süggendal, south Norway, by carbonic acid, evidenced by the occasional occurrence of calcite with the kaolin, though most of the metals of the alkalis and alkaline earths have been removed (as soluble carbonates) with the dissolved silica. Noteworthy also are the observations of Mr. R. A. F. Penrose, Jun., in his masterly account of the geology of the Cripple Creek district,² to the effect that kaolinization is the result of the rise of heated water from greater or less depths, and that the removal or kaolinization of felspar is a process that might be effected simply by carbon dioxide and water. The conclusions of these two authors with respect to the metasomatic effects of carbon dioxide are quite in accordance with those arrived at by other observers.³ Prof. C. Le Neve Foster⁴ states that emanations of carbonic anhydride are not unknown in Cornwall.

We have, furthermore, evidence as regards the nature of the kaolinizing agent in certain accessory constituents of metasomatic derivatives of granite such as luxulyanite. Though pyrite scattered sporadically and in some abundance among their finer constituents is not characteristic of Cornish granites, luxulyanite and many similar aggregates show by the presence of numerous cubic haematite and limonite pseudomorphs in their groundmass, sometimes associated with residual kaolin, that crystals of that sulphide were freely developed within them. If we assume that these crystals, like those occurring everywhere with the china-clay of the Cripple Creek district,⁵ were deposited by a kaolinizing solution, the probability is strong that carbon dioxide rather than any acid or other compound that would affect sulphide of iron occasioned the decomposition of the perished felspars. The evidence of two specimens from fresh-broken and unoxidized ground at Bedford United Mines, Devon, submitted to the Society—the one a much kaolinized fine-grained granite containing a fractured and altered felspar

¹ J. H. Collins, *Min. Mag.*, 1887, vol. vii, pp. 212–214.

² R. A. F. Penrose, 16th Ann. Rep. U. S. Geol. Surv., Pt. 2, 1895, p. 128 *et pass.*

³ See Sir Charles Lyell, 'Principles of Geology,' 1867, vol. i, p. 413; G. P. Scrope, 'Volcanos,' 2nd edit., 1872, p. 152.

⁴ C. Le Neve Foster, *Trans. R. Geol. Soc. Cornwall*, 1883, vol. x, p. 176.

⁵ Penrose, *loc. cit.*

phenocryst with enclosed pyrite, the other a greisen with bright mispickel and pyrite—seems conclusive on this point. The occurrence in kaolin of secondary pyrite and marcasite, forming granules, nodules, or veins, is noted by H. Rösler.¹ C. W. Schmidt² shows that in Iceland solfataric action has followed on the eruption of liparite, so that magnetite has been converted by hydrogen sulphide into pyrite. According to A. de Lapparent,³ the relatively acid extrusions are characterized by solfataric action and the basic by carboniferous emanations. With respect to the latter opinion, it is important to note a fact referred to by Signor Pietro Zezi,⁴ that the first gaseous emanations of volcanoes, e.g. hydrochloric and sulphurous acids, give place as volcanic activity diminishes to hydrogen sulphide and carbonic acid, both abundant in the springs of Sujo and in the Acque Albule, near Tivoli. We may hence be permitted to surmise that the kaolinization of the West of England granites, if wrought by a solution of carbon dioxide containing hydrogen sulphide, is evidence of solfataric action, and was therefore an occurrence somewhat late during the consolidation of those rocks.

The theory that the chief agent besides water that effected the kaolinization of the West of England granites was carbon dioxide disengaged during the metasomatism, by siliceous or acid solutions, of deep-seated calcareous killas or, less probably, dolomite or limestone⁵ receives some support from Sorby's discovery that sulphate of calcium and free hydrochloric and sulphuric acids are contained in the fluid of vesicles in the quartz of Cornish granites,⁶ and from the presence of calcium sulphate in the lode-water of some Cornish mines.⁷ The occurrence of calcite in lodes almost exclusively in the killas of the West of England, presumably owing to the leaching of calcium carbonate out of that rock by waters charged with carbon dioxide, is additional evidence in the same direction. Other relevant facts are the occurrence of pseudomorphs after datolite (a hydrated calcium boro-

¹ H. Rösler, *Neues Jahrb. Min.*, 1902, Beilage-Band xv, p. 276.

² C. W. Schmidt, *Zeits. Deutsch. geol. Ges.*, 1885, vol. xxxvii, p. 739.

³ A. de Lapparent, *Bull. Soc. Géol. France*, 1889, sér. 3, vol. xvii, pp. 286-287. Cf. J. W. Judd, *Quart. Journ. Geol. Soc.*, 1890, vol. xlvii, pp. 368-369.

⁴ P. Zezi, in 'The South Italian Volcanoes,' ed. by H. J. Johnston-Lavis, Naples, 1891, p. 83.

⁵ On Cornish calcareous rocks, see H. T. De la Beche, 'Report on the Geology of Cornwall, &c.,' 1839, pp. 79-89, *et pass.*

⁶ H. C. Sorby, *Quart. Journ. Geol. Soc.*, 1858, vol. xiv, pp. 471 and 487.

⁷ J. A. Phillips, *Phil. Mag.*, 1871, ser. 4, vol. xlii, pp. 408-413.

silicate) at Haytor, of abundant scheelite (calcium tungstate) in the lodes of the Peter-tavy district, and of axinite (hydrogen calcium aluminium borosilicate) in altered killas in numerous Cornish localities, and also in the Okehampton district, notably at Belston mine, with lime-garnet.

As to the important part played by carbonic acid in the alteration of Cornish rocks there is abundant testimony in the carbonatization of igneous dikes, noted by De la Beche¹ and by J. A. Phillips.² Many of such rocks, like the calc-dolerite of Three Bridges, Lewannick, effervesce freely when treated with acid.

There appears to be good ground for regarding the action of hydrofluoric acid on West of England rocks as deep-seated rather than superficial. The view that this acid or some of its compounds took part in the metasomatism of rocks containing calcium carbonate consorts with the opinion that the liquids discovered in cavities in topaz (a fluoriferous and hydrated aluminium silicate) are certainly in part carbon dioxide. One may remark, however, that the unaltered condition of the granophyric granite of the Mourne Mts., Ireland, in which only the biotite shows noteworthy change, is against the supposition that either that or any other similar topaziferous rock was permeated by hydrofluoric acid. It seems, indeed, quite probable that fluor-spar in solution, and not that acid, was the source of the fluorine of the schorl and apatite and even of the topaz of the tourmalinized and greisenized West of England rocks. Daubrée³ found that at Plombières hot springs arising in veins of fluor-spar had both deposited that mineral and, by action on bricks, formed near it crystals of apophyllite, which contains fluorine.

It appears indubitable, if the felspars of a tourmaline-granite be comparatively unaltered, that its magma evolved no free hydrofluoric acid at the time that its mica was being resolved into schorl. In the walls of fissures in the unmetamorphosed granite of Colkerrow quarry, Luxulyan, one finds large dark radiating crystals of tourmaline, and the same occur also upon the walls among the following grouped minerals:—quartz, orthoclase, albite, gilbertite (coating both orthoclase and tourmaline), lithia-mica, fluor-spar, apatite, lamellar calcite, and occasionally stilbite. The presence of the last three minerals contraindicates deposition with schorl from a hydrofluoric acid solution. On the other hand, we have in the occurrence together of the calci-

¹ H. T. De la Beche, *loc. cit.*, p. 88.

² J. A. Phillips, *Quart. Journ. Geol. Soc.*, 1878, vol. xxxiv, pp. 477, 482-484.

³ A. Daubrée, *Quart. Journ. Geol. Soc.*, 1878, vol. xxxiv, pp. 73-74.

ferous mica gilbertite, of calcium fluoride, calcium phosphate and fluoride, calcium carbonate, and a hydrated silicate of calcium and aluminium colour for the contention that the fissures were supplied from some profound source of both fluorine and calcium. The acidic character of the felspars of Cornish granites does not favour the supposition that their decomposition provided the calcium, but it might fairly be urged that a considerable amount of that element could have been derived from the altered plagioclase and augite of the pre-granitic dolerite dikes.

It is perhaps by the occurrence of fluor-spar in the West of England—in china-stone, greisen, and mineral-lodes (those of the Holmbush and Hingston Down mines in particular)—that the best presumptive evidence is afforded of the metasomatism of deep-seated calcareous rocks by hydrofluoric acid or other fluorine compounds. Subsidiary testimony is the very common occurrence of apatite in china-stone, gilbertite-rock, schorl-rock (that of Roche especially), many dolerites, such as the Trevone intrusive near Padstow, in the lodes of various mines, Fowey Consols for example, and in coarse tourmaline-granite at Bovey Tracey.

That the appearance of fluor-spar was not till somewhat late in the metamorphism of the West of England rocks, that is, during a period of dekaolinization, formation of schorl-rock and greisen, and deposition of tinstone and wolframite, but before a final influx of silica, is in accordance with the hypothesis that, roughly stated, the following sequence of events took place:—

Decarbonization of deep-seated calcareous rocks by acid waters, and resultant kaolinization by evolved carbon dioxide and increased porosity of neighbouring granite—partial in china-stone ('petuntzyte', Collins), and complete in typical china-clay rock ('carclazyte', Collins), with some erosion of primary tourmaline. Continued change of the aforesaid decarbonized and partially metasomatized calcareous rocks, containing, possibly, wollastonite, by solutions of boric acid or borates and hydrofluosilicic acid. Formation of fluor-spar and discharge of borated waters containing it by various outlets. Consequent dekaolinization in some areas of china-clay rock, and concomitant formation of a second and abundant growth of usually acicular schorl, mainly anterior to the deposition of silica derived from kaolin and additional sources, and in other areas deposition of fluor-spar, and formation of secondary mica and gilbertite with little tourmalinization. In the peripheral parts of granite bosses, where the movement of mineralizing waters seems to have been exceptionally free, there was gradual development of much

secondary mica and of topaz at the expense of kaolin, greisen resulting. Tinstone and wolframite seem to have been present in the dekaolinizing waters more especially at the period of final silicification of the metasomatized rocks.

The abundance of the supply of silica during the final stages of pneumatolysis in the West of England is well illustrated by the extraordinarily vesicular quartz-veins in connexion with some greisens and by the huge bulk of the matrix in proportion to its crystallized inclusions in the schorl-rock of Hornden Down. The evidence of the hornstone pseudomorphs after fluor-spar from Wheal Mary Ann, showing that the water bringing the silica acted as a solvent of the fluor-spar, warrants the suspicion that in trowlesworthite the spaces emptied of groundmass were occupied by fluor-spar before the advent of quartz, and that what, if any, erosion is visible where these two

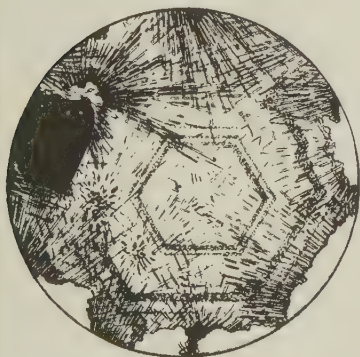


Fig. 3.—Zoned quartz with schorl; in luxulyanite.



Fig. 4.—Vesicular quartz zoned by tourmaline microliths; in greisen: Gunnislake Clitters mine, Cornwall.

minerals are in contact was occasioned by the siliciferous fluid. Daubrée showed¹ that silica (hyalite) and fluor-spar were deposited at Plombières by one and the same hot spring. The conjecture that in trowlesworthite the fluor-spar crystallized out before the quartz is strengthened by the fact that another Devon rock, a fluor-quartz-felspar veinstone from Brookwood mine, Buckfastleigh, much resembling trowlesworthite in appearance, exhibits phenocrysts of fluor-spar replaced centrally by quartz.

The removal of the groundmass of a granite, but not of its felspar

¹ A. Daubrée, loc. cit., p. 74.

phenocrysts, may be well seen in specimens adjoining the greisen at Kit Hill, Cornwall (fig. 5). In these, secondary mica is the equivalent of the acicular schorl of luxulyanite and trowlesworthite.

Granted that kaolinization preceded the deposition of secondary schorl in luxulyanite, trowlesworthite, and various other tourmalinized rocks, including some greisens, and that mica was eliminated and more or less feldspar was destroyed in this process, it is clearly unsafe to assume as certain that the brown and blue colours of tourmaline occurring therein are due to transmutation from biotite and feldspar respectively.¹ When, as in the granite of Cligga Head,² as also in that of Gunnislake, and in the greisen of Gunnislake Clitters mine (fig. 4), pale blue tourmaline micro-liths occur in the quartz (exactly similar in their disposition lengthwise parallel to the edges of crystals) and brown tourmaline crystals in the groundmass, it seems permissible to conclude that the solution yielding the brown tourmaline obtained, when it destroyed the mica, all the available bases that would yield a brown tint. In the Leather Tor schorl-rock there occur with tourmaline crystals that are wholly blue others that are brown within and blue without, suggesting, in accordance with Scharizer's analyses, that the tendency of titanium, calcium, magnesium, and fluorine to go out of solution to form tourmaline is greater than that of aluminium and the alkali metals. The mode of growth seems to be strictly in keeping with that of feldspars whose outer and inner zones differ in composition, and to be altogether analogous to that of orbicular diorite, in the magma of which the selection and the rejection of colouring material were carried on by hornblende and feldspar respectively in concentric areas.

Against these views the evidence of the coloration of the tourmaline in a great variety of West of England rocks appears to be absolutely conclusive. In one Dartmoor granite are seen tourmaline crystals having a blue centre, but zoned with brown externally, and a brown centre within a blue coating.³ A partly kaolinized granite from Tre-verbyn, St. Austell, contains tourmaline that is brown within and blue without and fringed with blue acicular crystals. Luxulyanite, moreover, which has been adduced as proof of the conversion of feldspar

¹ T. G. Bonney, *Min. Mag.*, 1877, vol. i, pp. 216-217.

² J. B. Scrivenor, *Quart. Journ. Geol. Soc.*, 1903, vol. lix, p. 151, and *Mem. Geol. Surv. Eng. & Wales, Geol. of Newquay*, 1906, p. 44.

³ W. C. Brögger (*Zeits. Kryst. Min.*, 1890, vol. xvi, p. 655) describes a tourmaline occurring in analcime and calcite at Langesundfjord, and showing, from within outwards, a blue nucleus, a deeper blue intermediate zone, and a brown marginal zone.

into blue schorl¹ may be ruled out of court if, as appears certain, kaolin was the origin of that mineral, most of the bases present in the schorl being supplied by the dekaolinizing fluid. Furthermore, examination of a series of microscopic sections of luxulyanite shows that the acicular schorl crystals not perched on the orthoclase phenocrysts or on the yellow eroded primary tourmaline, but arranged in tufts or spherules in the quartz, when viewed in their full length are both blue of various tints and pale brown. In some parts of a section opposed blue and brown tufts pass into one another; in others there is an approach to alternation of the two colours in groups of needles (sections of spherules), and many of the brownish groups are bluish at their origin. The distinctness of these colours might lead one to imagine that in a cooling menstruum two sets of microliths in a given area became pyroelectrically polar, and exercised a different selective action upon various dissolved bases. Fatal, however, to this notion appears the fact that, in places, some of the brown crystals viewed lengthwise and crossing others in the same plane at an obtuse angle give a blue tint where they intersect one another. The colours of the acicular schorl would seem, therefore, in this particular rock, to be considerably dependent on the absorptive and polarizing optic properties of the mineral, modified more or less by the nature and orientation of the medium, crystalline quartz, in which they are embedded. Doubtless the acicular crystals as a whole derived their aluminium from the kaolin of the groundmass as it was taken into solution. This opinion is strengthened by an examination of microscopic sections of the remarkable massive scoriaceous-looking tourmaline of Single Rose clay-work, St. Austell, to the history of which it may be well here to devote a few words. In this clay-work, where crystallization of schorl in place of the dissolved quartz and felspar of the groundmass had given a fair amount of solidity to the metasomatized rock before the destruction of the orthoclase phenocrysts, the hollow moulds of these phenocrysts became eventually filled with granular quartz and a little disseminated schorl, as in the case of some of the orthoclase crystals in a rock resembling luxulyanite, near Letcha farm, south-west of St. Agnes.² When, however, dekaolinization was rapid, and the supply of boron and basic material was long-continued and abundant, i. e. not less than about three parts by weight to two of combined and free silica in solution, enormous aggregates of quartzless schorl, containing

¹ T. G. Bonney, *Min. Mag.*, 1877, vol. i, pp. 216-217.

² C. Le Neve Foster, *Trans. R. Geol. Soc. Cornwall*, 1887, vol. x, pp. 8 and 9.

kaolin entangled in its meshes, were formed in cavities caused by the gravitation of masses of dekaolinized and disintegrated china-clay rock. Portions of a single block of this schorl proved to be a full load for a large barrow. The schorl was manifestly formed from a solution of kaolin to which the dekaolinizing agent supplied bases other than alumina. In microscopic section it presents blue, orange, and deep to light-brown crystals of many degrees of tint, showing both a brown nucleus enveloped in a blue subsequent growth and the reverse. It would appear, therefore, that when tourmaline is growing in the presence of a variety of dissolved metallic bases each crystal clears the solution of those bases that are in its immediate proximity.

Decrease of bulk first by kaolinization and then by some degree of dekaolinization, greatest near the contact-zone, sufficiently explains the



Fig. 5.—Granite with greisenized groundmass adjoining greisen: Kit Hill, Cornwall.

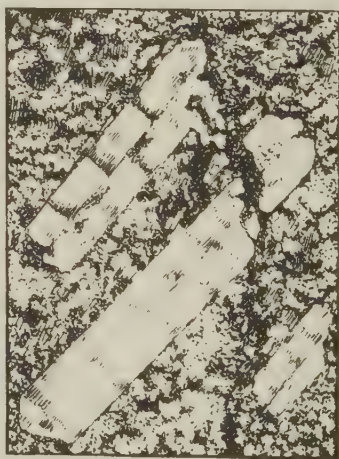


Fig. 6.—Shattered orthoclase in kaolinized schorlaceous granite: Treverbyn, Cornwall.

depressions of the surface of the country ('slads') over china-clay rock in the St. Austell district. Proof of movement of metamorphosed granite during solution of its kaolin and formation of schorl is furnished by specimens of schorlaceous partially kaolinized rock obtained from a well-sinking at Treverbyn. In this, owing to the setting up of new stresses by removal of support through dekaolinization, shifting and breakage of the partially altered orthoclase phenocrysts took place

(fig. 6). To the imperfect substitution of dissolved kaolin by mica and secondary quartz and resultant gravitation under the pressure of superincumbent masses may, in like manner, be attributed schistosity in Zinnwald greisen. The causation of settlement, or creeps, in the course of lodes by action such as dekaolinization may account also for the remarkable contortion, like that caused in boulder-clay by the melting of buried ice, and the brecciation observable in the country-rock of many of the St. Agnes and other West of England mines, Wheal Gurlyn for example.

There seems to be no cogent evidence against the theory, as regards the granites of the West of England, that the alkaline constituents of felspar together with more or less nascent silica, besides, in many instances, the quartz of the groundmass, were carried by the kaolinizing solution completely out of the field of action when not converted into gilbertite, lithia-mica, and other by-products. If so, the kaolin obtained its bases for the construction of schorl from a metasomatizing borated fluid later in date than that by which kaolinization was effected. In this connexion it is interesting to note that Mr. R. A. F. Penrose, Jun.,¹ remarks concerning the veins in the Cripple Creek district that they occupy fissures formed after considerable alteration of the country-rock, and that it is not impossible that the earlier metasomatizing solutions, which acted everywhere throughout the district, differed somewhat in their contents from the later ones, which seem to have acted only locally.

As the statement is still occasionally made that the kaolin of commerce is the result of subaerial action, it may be advisable, in closing this paper, briefly to formulate sundry facts that negative this supposition.

1. The researches of Sorby among others with respect to vesicular quartz, which was formed both before and after kaolinization, show that the West of England granite and its pneumatolysed derivatives cooled and consolidated under enormous pressure of superincumbent rocks—according to his calculations that of 32,400 feet in the St. Austell district.² Observations in mines indicate the general absence of surface- or ground-water in rocks below moderate depths (something like 2,000 feet at most, and in some regions 500 feet), ‘except in regions of expiring vulcanicity.’³ Surface-water, even if it descended to great depths, would produce most alteration in superficial rocks. Now the

¹ R. A. F. Penrose, *loc. cit.*

² H. C. Sorby, *Quart. Journ. Geol. Soc.*, 1858, vol. xiv, p. 494.

³ J. F. Kemp, *loc. cit.*, pp. 696–702 and 709.

solid granitic overburden covering good china-clay rock is frequently very slightly kaolinized, the felspar phenocrysts presenting a normal appearance within when fractured, as in the Caudle Down and Higher Nine Stones clay-works. The kaolin improves in quality with depth from the surface, and has been worked in the St. Stephen's district at 40 fathoms below it.

2. There is no evidence of abnormal rainfall in kaolin districts. The local and, within a given area, irregular kaolinization of granite suggests its production by some local cause and not by general atmospheric agencies. Satisfactorily to maintain the argument that kaolin was produced by weathering in other British granitic regions, but was removed thence by glacial action, which did not affect Cornwall and Devon, necessitates the discovery of causes why much of the granite of those counties is unkaolinized and why kaolinized rock elsewhere, however deep, has been removed without leaving some remnants, even under crags facing down stream in the line of glacial flow.

3. A local and sufficient cause of kaolinization is known to exist in the ascent of heated solutions through the rocks of various districts, as, e.g. the rhyolites of the Yellowstone National Park.

4. Weathered granite, Rösler points out (*loc. cit.*), breaks up into imperfectly altered fragments ere final disintegration; also its ground-mass felspars suffer from kaolinization before its phenocrysts, the reverse being true of granite kaolinized from below.

5. Kaolinization has been commonly accompanied or followed by the production of many minerals that could not have originated in surface-material—schorl, fluor-spar, tinstone, and topaz, among others.

It remains only to express the author's indebtedness to his friend, Mr. George Wilson, for his careful delineation of the structures shown in the figures accompanying this paper.

On the possible existence of a nickel-iron constituent (Fe_5Ni_3) in both the meteoric iron of Youndegin and the meteoric stone of Zomba.

By L. FLETCHER, M.A., F.R.S.

Keeper of Minerals in the British Museum.

[Read June 16, 1908.]

IN a paper read before the Mineralogical Society on April 10, 1894,¹ describing the details of the analysis of a meteoric stone which had been found at Makariwa in New Zealand, attention was called by the present author to the fact that the operation of extracting the nickel-iron by mercuric solution from the material separated from the powdered stone by the magnet was scarcely a terminable one; for even the twelfth extraction by means of a solution of mercuric ammonium chloride evidently contained an appreciable amount of colouring matter, while the colour of the extract indicated an increase in the proportion of the nickel. 'It was clear that one or other constituent of the attracted material was being only slowly dissolved, and that it was practically useless to push the operation farther. It was inferred from subsequent observations that the continued extraction was due to the presence of particles of nickel-iron and metallic nickel partially protected from the mercuric solution by adherent rust' (p. 293).

As the meteoric stone of Makariwa had been long buried in the earth and was evidently 'weathered', there was no doubt about the fact of the rusting. It was inferred that the iron had been more affected than the nickel during the weathering, and that the metallic iron was more quickly brought into solution than the metallic nickel by the mercuric liquid, the later extracts thus being richer than the earlier ones in the latter constituent (p. 319).

The same fact was observed, some years later, during the extraction of the nickel-iron from a meteoric stone which had fallen at Zomba, British Central Africa, and the observation was recorded in a paper

¹ Min. Mag., 1894, vol. x, p. 287.

read before the Society in the year 1900.¹ There was again no doubt that, as the extraction proceeded, the extract became richer in nickel, and that complete extraction would require too numerous a set of solvent operations to be practicable in the course of a quantitative analysis. But in this case the meteoric stone was a fresh one, not having been rusted through exposure to the weather.

The ten extracts obtained by means of the mercuric solution were collected into two sets.

1. The first set consisted of the seven extracts made before the attracted material had been heated to redness in a current of hydrogen; it gave the following numbers (p. 35):—

Nickel-iron. gram	Fe. gram	Ni(Co). gram	Percentage of Ni(Co).
0.3908	0.3423	0.0485	12.41

2. The second set consisted of three additional extracts obtained from the material which remained after the preceding seven extractions, the material being in each case first heated to redness in a current of hydrogen; this set gave (p. 35):—

Nickel-iron. gram	Fe. gram	Ni(Co). gram	Percentage of Ni(Co).
0.0442	0.0307	0.0135	30.54

The residue from these ten treatments was submitted to the action of hydrochloric acid and completely analysed; the numerical results were found to correspond to a large amount, namely 0.2529 gram, of silicates, admixed with a small amount, namely 0.0187 gram, of nickel-iron, the latter having the following composition (p. 35):—

Nickel-iron. gram	Fe. gram	Ni(Co). gram	Percentage of Ni(Co).
0.0187	0.0115	0.0072	38.50

The total amount of nickel-iron from the two sets and the residue was thus:—

Nickel-iron. gram	Fe. gram	Ni(Co). gram	Percentage of Ni(Co).
0.4537	0.3845	0.0692	15.25

The most simple and obvious interpretation of the above numbers is that the nickel-iron of the Zomba meteorite contains a constituent having 38.50 per cent. of nickel, and that the said constituent is less easily affected than the rest of the nickel-iron by the mercuric solvent.

¹ Min. Mag., 1901, vol. xiii, p. 1.

But the same kind of result having been regarded as due to slow rusting in the case of Makariwa, and it being conceivable in the case of Zomba that many of the particles of nickel-iron (some no doubt of so small a size that they become immediately oxidized on coming into contact with the air), might have quickly rusted during the filtrations, notwithstanding all the care that had been taken, the explanation given in the case of Makariwa was extended to that of Zomba, and it was pointed out (p. 35) that:—

‘The variation of the percentage of Ni(Co) from 12·41 to 38·50, as the extraction proceeds, does not necessarily imply the existence of different alloys of nickel-iron in the material; it is probably a mere result of the easier oxidation of the iron than the nickel during exposure of the alloy to the atmosphere in the course of the operations.’

Having occasion lately to read through the paper once more, the author perceived that the explanation there suggested by him is untenable. It is true that some of the particles of nickel-iron are of so small a size that they must become oxidized, when magnetically separated from the powdered stone and exposed to atmospheric action. The explanation thus introduces a *vera causa*, and one which accounts both for the increase of the percentage of nickel during the first set of seven extractions, and for the increase of the extracted nickel-iron which follows the heating in a current of hydrogen; but the cause is not quantitatively sufficient to account for all the facts observed. For the iron rusted through atmospheric exposure of the nickel-iron particles after magnetic separation from the powder, or after being subjected to the mercuric solvent, must all have gone to the increase of the iron in the second set of extracts and in the final residue. The latter, therefore, should each have yielded smaller percentages of nickel than 15·25, the amount calculated to be present in the unruined nickel-iron; on the contrary, they actually yielded larger percentages, namely 30·54 and 38·50 respectively.

The published explanation thus being untenable, the author is compelled to infer that the analytical operations had been more successful than he had thought possible at the time; that the rusting during the operations, instead of being appreciable, was really small in amount; that in the unruined nickel-iron particles of the Zomba meteorite there is actually a constituent containing about 38·50 per cent. of nickel; and that this particular constituent is only slowly acted upon by the mercuric solution. In the original paper (p. 12) mention was made of the

presence of bright metallic spangles among the grains of the silicate residue after the ten mercuric treatments; and it was suggested that they might be schreibersite, but merely because they were in small proportion and had remained undissolved by the mercuric solution; they were more probably thin plates of the hypothetical nickel-rich constituent.

And in a paper on the Youndegin (Western Australia) meteoric iron¹ read in 1899, only a few months before, the author had given an account of an apparently homogeneous constituent having almost precisely this percentage composition. From 97.25 grams of that meteoric iron there was obtained 0.087 gram of a constituent which was not easily soluble in very dilute hydrochloric acid; on analysis of 0.0621 gram it was found to contain 38.13 per cent. of nickel. The substance corresponded in mode of occurrence and chemical composition to the constituent of meteoric iron known as taenite, for which various percentages of nickel (from 13.02 to 48.61) had already been assigned. The compound Fe_5Ni_3 would contain 38.61 per cent. of nickel; having regard to the small amounts of metallic material analysed, namely, 0.0621 gram in the case of Youndegin and 0.0187 gram in the case of Zomba, the numbers 38.13 and 38.50, obtained for the Youndegin and Zomba constituent respectively, are remarkably close to the number 38.61 required by the above formula.

Recently Dr. S. W. J. Smith, of the Imperial College of Science and Technology, has brought to a conclusion a long series of investigations of the thermo-magnetic characters of the Sacramento meteoric iron²; and can only interpret his results by imagining the Sacramento meteoric iron to consist of plates of a nickel-poor constituent, kamacite (containing 6 or 7 per cent. of nickel), interrupted by plates of a nickel-rich constituent, taenite, containing about 27 per cent. of that metal.

But he infers from his thermo-magnetic observations that the taenite of the Sacramento iron is itself composite, and that it consists of kamacite admixed with a nickel-iron constituent containing not less than 37 per cent. of nickel; and he calls attention to the fact that, according to the analyses already published, taenite mechanically extracted from meteorites contains from 25 to 30, or approximately 27 per cent., of nickel, while taenite chemically extracted always contains a higher percentage, and in the case of Youndegin as much as 38.13 per cent. In only a single instance, that of Beaconsfield, the per-

¹ Min. Mag., 1899, vol. xii, p. 171.

² Philosophical Transactions, 1908, ser. A, vol. ccviii, p. 21.

centage of nickel in the corresponding thin plates has been found to be above 38 (in fact, 48.61). Further, Dr. Smith suggests that taenite as it exists in meteorites in general has an approximately constant composition, not because it is a definite compound, but because it is really a eutectic substance, and that it is an intimate mechanical mixture, in fixed proportion, of thin plates of a nickel-poor constituent (kamacite) and thin plates of a nickel-rich constituent (containing not less than 37 per cent. of nickel). Hitherto Mr. F. Osmond and others have regarded the plessite, not the taenite, of meteoric iron as being of eutectic character.

In the description of the small, thin plates extracted by the author from the meteoric iron of Youndegin, he stated as follows (p. 173):—

‘It may be mentioned that during the determination [of the specific gravity of the taenite which had become oxidized during the eleven years which had passed since its isolation] great difficulty was experienced in removing all the interpenetrant air; the plates were composite, and the air was only slowly removed from the intervening spaces by an oft-repeated use of the air-pump.’

It may thus be a fact that the dilute hydrochloric acid, used for the extraction of this material from the meteoric iron, had at the same time removed plates or patches of kamacite of microscopic thinness which had been present between, or within, the thin plates of nickel-rich constituent, and that the composite plates, as present in the meteorite, were not merely a mixture but, as suggested by Dr. S. W. J. Smith, a eutectic mixture.

The percentage composition assigned to kamacite (6 or 7 per cent. of nickel) corresponds to the formula Fe_{15}Ni (which requires 6.53 per cent. of nickel); hence, if the results obtained for Youndegin and Zomba are true for meteorites in general, the nickel-poor constituent (kamacite) and the nickel-rich constituent of meteoric iron would be respectively Fe_{15}Ni and $\text{Fe}_{15}\text{Ni}_9$; if Fe_5 be denoted by A, and Ni by B, the formulae are symmetrical, namely, A_3B and AB_3 .

If taenite is really a mixture of these two constituents and contains about 27 per cent. of nickel, 4 parts by weight of kamacite (containing 6.53 per cent.) must be mixed with 7 parts by weight of the nickel-rich constituent (containing 38.61 per cent.); for the percentage of nickel for such a mixture would be 26.94.

The results obtained for the meteoric iron of Youndegin and the nickel-iron extracted from the meteoric stone of Zomba are in such remarkably close agreement both with each other and with the formula

Fe_3Ni_3 , and the observation relative to the structure of the thin plates extracted from the Youndegin meteorite is in such close agreement with Dr. S. W. J. Smith's interpretation of the compositeness of taenite in general, that it seems worth while to direct special attention to them; still, it must be remembered that the material analysed was very small in quantity and that the taenite of one mass (Beaconsfield) has been found to contain a much higher percentage (48.61) of nickel. As the Beaconsfield and Cranbourne masses belong almost certainly to the same fall, and the taenite of Cranbourne has been found to be normal in chemical composition, confirmation of the Beaconsfield determination is desirable; the iron was in that case determined only by difference, and it is possible that the taenite had been to some extent rusted, for it was obtained from rusted fragments of the mass.

Note on synthetical corundum and spinel.

By G. F. HERBERT SMITH, M.A., D.Sc.

Assistant in the Mineral Department of the British Museum.

[Read November 12, 1907.]

DURING recent years a considerable industry has grown up at Paris in the synthetical manufacture of corundum for jewellery purposes by means of the process devised by Professor A. Verneuil.¹ In place of the fragments of natural ruby used in previous attempts, ammonium-alum is the material employed. After careful preparation to free it from potash and other impurities, it is ground to a powder and placed in a sieve at the top of the oxygen tube of an inverted blowpipe. The sieve is tapped by a hammer at regular intervals, and uniformity is in this simple way produced in the amount of powder that falls; the necessary adjustment is effected by varying the height through which the hammer falls. To minimize the cost of production, a few alterations have been made in the original apparatus. The hammer is no longer actuated by the make and break of an electro-magnet, but is directly operated by a cam, and for further simplicity the cams of several machines are worked by the same shaft. Coal-gas has been substituted for hydrogen, and has been found equally effective. The process is now so simple that one man can look after a dozen or more of these machines.

As soon as the powder reaches the orifice of the pipe, the ammonium volatilizes in the flame, and the alumina falls as a liquid drop on to a narrow pedestal of previously fused alumina. By turning a screw which lowers this pedestal the operator causes the alumina mass—'boule,' as it is termed by the French jewellers—to grow upwards. The pressure of the effluent gases is kept low at first lest the pedestal be melted, and is afterwards gradually increased so that the growing mass takes the shape of a pear. The orifice is carefully jacketed to prevent too sudden cooling of the drop and consequent disastrous flaws.

¹ A. Verneuil, 'Mémoire sur la reproduction artificielle du rubis par fusion.' *Annales de chimie et de physique*, 1904, sér. 8, vol. iii, pp. 20-48; also reprinted with separate pagination, Paris, Gauthier-Villars, 1904, pp. 1-30. An abstract appeared in *La Nature*, Paris, 1904, vol. xxxii, pp. 177-178.

It is, indeed, a most surprising fact, as was pointed out by Professor G. Wyrouboff,¹ who examined some of the early specimens, that these drops have a homogeneous crystalline arrangement and are not, as might have been anticipated, an alumina glass or an irregular aggregation of crystalline fragments. The principal crystallographical axis is parallel to the core of the pear, if the drop has been properly prepared. The surface at the side is clear and vitreous in lustre, but shows horizontal striae due to slight variation in the density of the colouring matter. The broad end likewise becomes clear and vitreous if allowed to remain in the flame, but this does not as a rule happen, since for the sake of economy the gases are cut off as soon as the drop is large enough. When the end is rough, examination with a lens shows that it is covered by a fine network of lines mutually intersecting in angles of apparently 60° . To see what relation the network bore to the crystallographical constitution, I placed a well-formed drop on a goniometer, and found that the reflections obtainable corresponded exactly in position to the faces of the fundamental rhombohedron, $r=(100)=(10\bar{1}1)$, of corundum. I may also mention that the apex of the pear which is broken on removal from the pedestal sometimes shows a good plane of parting parallel to the basal plane.

These drops are colourless, or, if not quite free from potash, slightly brownish in tint. The particular hue known as pigeon's-blood red is obtained by the addition of sufficient chrome-alum to give $2\frac{1}{2}$ per cent. of chromic oxide in the fused mass. With a smaller quantity, pink stones have been produced; from their similarity in colour to the so-called 'burnt' topazes, the original colour of which has been altered to pink by the application of heat, they have been most unhappily termed in the jewellery trade 'scientific topazes'.

Since the stones thus synthetically formed have the actual structure of natural corundum, it necessarily follows that they possess all its physical characters—refractive power, double-refraction, dichroism, hardness, &c.—and that they cannot therefore be distinguished from it by any of the ordinary tests. Experience, however, has shown that these stones, as at present manufactured, are never free from included air-bubbles and curved striae, and thus they may easily be discriminated upon examination with a microscope or a lens. In natural corundum the cavities are negative crystals and have plane sides, and the striae are straight.

It is not a little surprising that all efforts to impart to these syn-

¹ See memoir mentioned in preceding footnote, pp. 25-27 of the reprint.

thetical stones a blue colour, and thus to obtain sapphire, have as yet been attended with failure. At the end of October, 1907, I received from Mr. E. Hopkins, 58 B Hatton Garden, London, E.C., a specimen, in the familiar pear-shape, of what is termed by American jewellers 'Hope sapphire', presumably from fanciful analogy with the famous blue diamond. Mr. Hopkins had himself detected that it lacked the dichroism of sapphire, and in hardness lay between sapphire and topaz. From an observation made with a refractometer upon a small polished facet, I determined the refractive index for sodium-light to be 1.727, and on placing the specimen between crossed nicols found that it had no action upon polarized light. Further, I noticed that the fine network of lines covering the broad end of the pear mutually intersected at right angles at the top, the angle diminishing to 60° at certain regions of the sides. Goniometrical examination showed that the reflections corresponded mainly to the faces of the octahedron, and in a lesser degree to those of the cube, the crystallization being cubic. The obvious conclusion that these blue stones are synthetical spinel was confirmed by Dr. G. T. Prior, who found by a qualitative chemical examination that they consisted of alumina and magnesia with a trace of cobalt.

COMMUNICATIONS FROM THE OXFORD MINERALOGICAL
LABORATORY. No. XII.

*On the structure of Perovskite from the Burgumer Alp,
Pfitschthal, Tyrol.*

By H. L. BOWMAN, M.A.

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[Read January 21, 1908.]

I. INTRODUCTORY AND HISTORICAL.

THE question of the system to which perovskite should be referred, and the explanation of the discrepancy between its form and optical properties, have been the subject of much discussion among crystallographers ever since the discovery by Des Cloizeaux, in 1858, of the double refraction of crystals of calcium titanate from Zermatt, having the same composition as the crystals of cubic form from the Ural Mountains, to which the name perovskite had been given by G. Rose in 1839.

It is unnecessary here to give in detail the earlier history of the controversy, as a full account of this has already been published in monographs by A. Ben Saude¹ and P. J. Holmquist,² but it will be necessary to refer in some detail to the later work by Baumhauer,³ Ben Saude, and other writers.

The material previously investigated has been derived principally from four sources:—the Ural Mountains, Zermatt, the Pfitschthal in Tyrol, and Arkansas. The crystals are all of cubic habit, with the

¹ A. Ben Saude, 'Über den Perowskit.' Preisschrift, Göttingen (Dieterich'sche Buchdruckerei), 1882. Reviewed by Tschermak (Min. Petr. Mitt., 1882, vol. v, p. 194); by Baumhauer (Zeits. Kryst. Min., 1883, vol. vii, p. 612); and by Klein (Neues Jahrb. Min., 1884, vol. i, p. 175).

² P. J. Holmquist, 'Synthetische Studien über die Perowskit- und Pyrochlor-mineralien.' Inaug.-Diss., Upsala, 1897; Bull. Geol. Inst. Univ. Upsala, 1897, vol. iii, pp. 181-268.

³ H. Baumhauer, Zeits. Kryst. Min., 1880, vol. iv, p. 187.

exception of those from Arkansas, which are octahedral. These latter are, however, perhaps not true perovskite, as they have been found by Mar¹ to contain niobium and tantalum, and to be intermediate between perovskite and dysanallyte.

There is a general agreement among observers that, geometrically, the crystals of perovskite are referable to the cubic system; a number of forms having been described, whose faces, though in many cases not holohedrally developed, are yet similarly distributed about the three axes, in accordance with cubic symmetry.

The optical properties have been examined in detail, more particularly by Des Cloizeaux² and Ben Saude³, who agree in finding the crystals strongly birefringent and biaxial. All the crystals, with the exception of those from Tyrol (see p. 159), are described as having in places a more or less regular lamellated structure parallel to the faces of the cube, with extinction parallel to the diagonals of the cube-faces, and showing in convergent polarized light hyperbolic brushes, like those observable in plates perpendicular to a third mean line. In other places there are diagonal lamellae showing a single, normally-emergent (biaxial) optic axis.

The method of etching was first applied to these crystals by Baumhauer,⁴ and the etching figures were studied in connexion with the optical properties by himself and by Ben Saude. These observers obtained on the cube-faces, by means of hydrofluoric acid, two distinct types of etching pits in different parts, viz:—

(a) rhombic pits, which lie in symmetrical positions on adjacent lamellae parallel to cube-faces;

(b) linear or elongated pits, lying parallel to cube-edges and in two mutually rectangular positions on adjacent diagonal lamellae.

The shapes of the linear pits described by the two authors are somewhat different, probably owing to the use by the former of reflected light, a method which (as pointed out by Ben Saude) is wanting in precision. The orientation of the rhombic pits is also differently stated by them, those observed by Baumhauer being symmetrical to

¹ F. W. Mar, *Amer. Journ. Sci.*, 1890, vol. xl, p. 403. See also C. Hintze, 'Handbuch der Mineralogie'. 1897, vol. ii, p. 1651.

² A. Des Cloizeaux, *Ann. d. Mines*, 1858, sér. 5, vol. xiv, p. 417; *Nouvelles Recherches*, 1867, p. 84; *Mém. de l'Acad. Française*, 1868, vol. xviii, p. 594; *Neues Jahrb. Min.*, 1875, p. 279, 1877, pp. 160 and 503, 1878, p. 43; *Bull. Soc. franç. Min.*, 1893, vol. xvi, p. 218.

³ A. Ben Saude, *loc. cit.*, p. 15.

⁴ H. Baumhauer, *loc. cit.*

the cube-diagonals,¹ while those described by Ben Saude had one of their edges parallel to an edge of the cube.

The areas showing these two types of pits coincide with those defined by the optical characters. Ben Saude found, however, by using high magnification, that the lamellae with rhombic pits are themselves composed of narrower lamellae, which show different colours and sometimes slight differences of extinction, and that the pits extend across these without disturbance.

Treatment with fused caustic potash, on the other hand, gave rise to square pits with edges parallel to the diagonals of the cube-face, in place of the rhombic pits produced by hydrofluoric acid.

Etching figures on faces of the dodecahedron or octahedron were not obtained by these observers; but sections parallel to the dodecahedron, examined by Ben Saude, showed in polarized light three kinds of areas, viz.:—

- (1) areas extinguishing parallel to the intersections of the face with the cube, and showing a normally-emergent bisectrix;
- (2) (3) Two sets of bands lying at about 58° to the cube-edge in either direction, and extinguishing at 45° to that edge.

The observations of Baumhauer and Ben Saude were thus in most respects in agreement, but the explanations of the structure proposed by them were widely opposed.

Baumhauer, adopting the view proposed by Des Cloizeaux,² considered the crystals to be mimetic and to consist of orthorhombic material, the (pseudo)-cube being in reality a combination of an orthorhombic prism $\{110\}$ and the basal pinacoid $\{001\}$, with a prism-angle of 90° (corresponding to the axial ratios, $a:b:c = 1:1:0.7071$), and the lamellation being due to twinning on the faces of $\{111\}$. He also described the existence of twinning on faces of $\{110\}$. The rhombic etching pits would then be characteristic of $\{001\}$,³ while the linear pits would indicate the prism-faces. The optic axial plane would be parallel to (001) , and the axial angle $2V = 90^\circ$, so that one optic axis emerges perpendicular to each prism-face.

¹ H. Baumhauer, *Zeits. Kryst. Min.*, 1880, vol. iv, pp. 189, 197; and 1888, vol. vii, p. 612.

² A. Des Cloizeaux, *Neues Jahrb. Min.*, 1878, p. 48.

³ Ben Saude laid stress on the orientation of these pits, as observed by himself and (as he supposed) also by Baumhauer, not being in accord with the symmetry of the basal pinacoid of an orthorhombic crystal. Baumhauer, however, explained later (*Zeits. Kryst. Min.*, vol. vii, p. 612) that the pits observed by him were as above described, and had been wrongly drawn in *Zeits. Kryst. Min.*, vol. iv, plate 7, figs. 1 and 8.

Tschermak also considered perovskite to be mimetic, and in a review of Ben Saude's work¹ drew from his observations the conclusion that it belonged to the monoclinic system, and that the (pseudo)-cube was composed of the forms $\{100\}$, $\{001\}$, and $\{010\}$, the first two having linear, and the last rhombic pits; with lamellated twinning on (100), (010), and the prism-faces. This removal of perovskite to the monoclinic system was suggested in order to account for the orientation of the rhombic pits described by Ben Saude.

Ben Saude, on the other hand, rejected Baumhauer's view, chiefly owing to his observation that where the lamellae are crossed by a crack they frequently show a sudden change in breadth and in their polarization-colours²—a character which he held to be incompatible with their being crystalline individuals in twin position, and to mark them as of secondary origin, and as not belonging to the substance in its original condition. He considered the etching figures to be untrustworthy as evidence of the symmetry of the crystal, on account of the (supposed) difference in the symmetry of the pits produced by different solvents, and of the extension of the pits across the optical boundaries. He concluded that perovskite was in fact cubic (pyritohedral), and that the double refraction was produced 'durch Änderung der ursprünglichen Gleichgewichtslagen beim Wachsthum der Krystalle'.

As pointed out by Mallard,³ this conclusion hardly seems to follow from the observations described, which rather indicate that 'all crystals of perovskite, from whatever locality, possess exactly the same optical ellipsoid, orientated in the same manner', and since the form and position of this ellipsoid are thus characteristic of perovskite, the internal structure of the crystals must be orthorhombic and not cubic.

Inasmuch as the observations described below tend to confirm the correctness in essential points of the explanation given by Baumhauer, the relations which should exist between the etching figures on the cube-faces and the orientation of the indicatrix, in the different portions of crystals twinned in accordance with it, are given for reference in figs. 1 and 2.

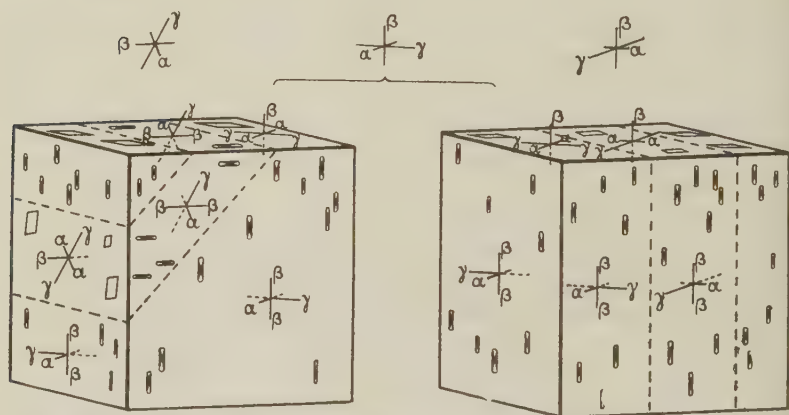
The specimens of perovskite hitherto described from the Tyrol have been found to differ markedly from the above, both in structure and optical properties. They are three in number, viz.:—

¹ G. Tschermak, *Min. Petr. Mitt.*, 1882, vol. v, p. 194.

² A. Ben Saude, *loc. cit.*, p. 15. It seems possible, however, that this behaviour of the lamella might occur in a polymorphous crystal, in which cracks existed before the change of state.

³ E. Mallard, *Bull. Soc. franç. Min.*, 1882, vol. v, p. 234.

- I. A single small crystal 'from the Wildkreuzjoch', described by Hessenberg in 1861,¹ and examined later optically by himself and von Fritsch,² by Des Cloizeaux,³ and by Klein.⁴
- II. A few small crystals on a chip of rock, probably from the same locality, described by vom Rath⁵ and by Hessenberg,⁶ but not optically examined.
- III. Small crystals of 'perovskite from Pfitsch', examined by Klein.⁷



Perovskite: orthorhombic combination $\{110\} \{001\}$ showing etching figures and orientation of the axes of the indicatrix.

Fig. 1.—Twinned on $(1\bar{1}1)$.

Fig. 2.—Twinned on $(1\bar{1}0)$.

These all showed cubic forms, like other specimens of perovskite, but had a *diagonal* lamellation only, and were optically biaxial with a positive acute bisectrix of narrow angle perpendicular to the faces of the cube. It was suggested by Ben Saude that the crystal I might not really be perovskite; but crystals from III were found by Klein to have—at least qualitatively—the composition of that mineral. The optical characters of these crystals were interpreted by Mallard,⁸ as due to the crossing of lamellae of the more ordinary variety of perovskite.

¹ F. Hessenberg, Abhandl. Senckenberg. naturf. Ges., 1862, vol. iv, p. 20.

² F. Hessenberg, *ibid.*, 1872, vol. viii, p. 38.

³ A. Des Cloizeaux, Neues Jahrb. Min., 1877, p. 160.

⁴ In Ben Saude, *loc. cit.*, p. 33 (note).

⁵ G. vom Rath, Ann. Phys. Chem. (Poggendorff), 1872, ser. 5, vol. xxiv, p. 595.

⁶ F. Hessenberg, Abhandl. Senckenberg. naturf. Ges., 1872, vol. viii, p. 407.

⁷ C. Klein, Neues Jahrb. Min., 1884, vol. i, p. 245.

⁸ E. Mallard, Bull. Soc. franc. Min., 1886, vol. ix, p. 60.

The problem presented by perovskite falls naturally into two parts:—

- (1) The determination of the system to which the substance belongs—whether it is cubic, as indicated by its form, the birefringence being due to strain; or forms mimetic crystals built up of lamellae of lower symmetry corresponding with the optical characters.
- (2) The discovery of the causes which have brought about this discrepancy between the form and the optical characters.

In the present paper, the first only of these questions has been considered.

II. PEROVSKITE FROM THE BURGUMER ALP.

Some of the chief difficulties hitherto encountered in the determination of the optical properties of perovskite, have been due to the imperfect transparency of the crystals coupled with their complex lamellated structure.

The object of the present paper is to describe the characters observed in a series of exceptionally good and transparent crystals from the Burgumer Alp in the Pfitschthal, Tyrol, which were kindly placed at the author's disposal by Professor P. von Groth, in whose laboratory the earlier portion of the work was carried out.

The Burgumer Alp lies at the foot of the Wildkreuzjoch, and blocks of rock are often found there which have fallen from above. Hence 'Burgumer Alp' must be taken to indicate the same place of origin as 'Wildkreuzjoch', the locality given for the crystal described by Hessenberg. In view of this fact, the differences between the crystals here described and those of Hessenberg, vom Rath, and Klein, are the more remarkable.

The crystals are cubic in habit—often somewhat irregular, owing to the parallel growth of two or more smaller cubes, or cavernous—dark brown, and brilliant; and the largest examined was about $2\frac{1}{2}$ mm. in its greatest dimension. Besides the cube, the dodecahedron is frequently present, and small faces of the octahedron also occur. There are also a number of other forms, but, owing to the striated nature of the faces, they cannot be determined with any certainty. On one crystal a large face, near the dodecahedron, to be referred to later, makes an angle of about 33° with a cube-face, and may belong to the form $g\{320\}$ which has been previously observed on perovskite ($100:320 = 33^\circ 41'$).

The cube-faces generally show sharp, straight striae, parallel to one or other of their edges, those on different parts of the face being

mutually perpendicular. On some crystals the two sets meet along a diagonal line. Dodecahedron-faces also are often crossed by two sets of lines at right angles, parallel and perpendicular to their intersections with the cube.

After measurement, several of the crystals were etched by immersion for $1\frac{1}{2}$ hours in dilute hydrofluoric acid, and the faces examined by reflected light under a magnifying power of 450 diameters. For this purpose a Zeiss 16 mm. (Ap. 0.30) objective and deep eyepiece (Zeiss 18, 10 mm.) were used, as with this arrangement the working distance is sufficiently long to allow the crystal, mounted in a slightly inclined position on a horizontal axis on the stage, to be illuminated directly by daylight.

The pits produced on the cube-faces are seen to be of two types: (1) square or rhomb-shaped, (2) elongated or linear, and the faces are mapped out into areas of two kinds distinguished by the shape of their pits. On most of the plates examined (cf. fig. 3), areas with pits of type (1) were predominant, usually with more or less irregular or wedge-shaped strips showing linear pits scattered through them (as at *b*, *c*). Some few, however, were almost entirely occupied by linear pits (cf. fig. 7).

Drawings were made of the best faces, to show the distribution of the pits, and the crystals were then sliced parallel to these faces, in such a way as to preserve the etched surface for examination by transmitted light.¹

The plates, which are from 0.2 to 0.7 mm. thick, appear quite transparent (except where flawed) and of a light brown colour, and are excellently suited for optical examination under the microscope. Nine plates in all were prepared, of which seven were parallel to cube-faces, while two were respectively parallel to an octahedron-face and to the face (320) ? mentioned above.

Plates parallel to faces of the cube.

Division into dissimilar areas.—On examination of plates parallel to cube-faces, under the microscope between crossed nicols, two kinds of areas are at once distinguishable, viz. :—

- (1) areas showing no interference-colour, extinguishing perfectly at about 45° to the cube-edges, but giving no interference-figure in convergent light ;

¹ This work was carried out very skilfully by Messrs. Voigt and Hochgesang of Göttingen.

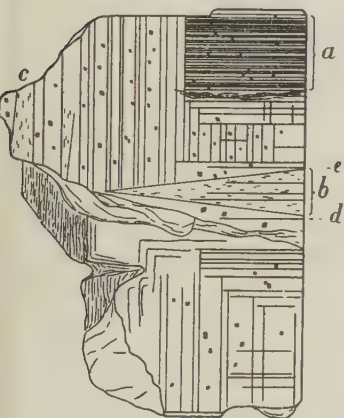
(2) areas showing colours of low order, and in convergent light a single, biaxial optic axis perpendicular to the face. The interference-figure is very well defined, and shows strong axial dispersion, the brush being coloured red on the positive side of the figure. The direction of the brush indicates that the plane of the optic axes is parallel to a cube-edge.

These areas coincide with those defined by the etching figures; rhombic or rectangular pits being found on the former (1), while linear pits occur on the latter (2). These two kinds of areas will be hereafter referred to by the letters *C* and *M* respectively. Thus:

M-areas have linear pits, and are perpendicular to an optic axis;

C-areas have rhombic or rectangular pits, and extinguish at 45° .

A typical plate of this kind is shown in fig. 3.



Perovskite: plates parallel to cube-faces.

Fig. 3.—Showing *C*- and *M*-areas, with cubic lamellae and oblique *C-M*-junctions.

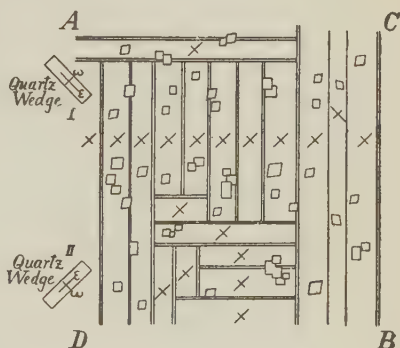


Fig. 4.—Arrangement of bands and etching pits on *C*-area.

By the help of the stage-goniometer designed by Professor Miers,¹ the junctions between the *C*- and *M*-areas may be traced across an edge, and the relations of the pits on adjacent cube-faces determined. An *M*-area, whose pits are parallel to the edge, is found to have a similar *M*-area adjacent to it; while an *M*-area, whose pits are perpendicular to the edge, has a *C*-area adjacent to it, and vice versa.

Lamellation of C-areas.—The *C*-areas are almost always divided into broad strips by strongly marked lines or narrow bands parallel to the

¹ See H. A. Miers, 'Mineralogy'. 1902, fig. 364, p. 178.

cube-edges. These are of the same colour as the broad strips, but usually appear brighter, and change in brightness when the mirror is moved so as to give oblique illumination, while at the same time the adjacent broad strips develop a remarkable fluted appearance. The narrow bands have the appearance of thin plates of dissimilar material, about 0.001 to 0.003 mm. thick, arranged parallel to the cube-faces and perpendicular to the surface of the plate (cf. fig. 4). The width of the broad strips varies up to about 0.2 mm. Rarely, a *C*-area is almost entirely free from lamellae (as at *a*, fig. 7).

On inserting a quartz-wedge¹ along one of the cube-diagonals, a section (fig. 3) of 0.624 mm. thickness shows compensation on a *C*-area at about the eighteenth order, indicating a birefringence of about 0.017 for sodium-light. The whole of the area is usually compensated at the same time, when the quartz-wedge is inserted along *AB* (position I, in fig. 4), while the insertion of the quartz-wedge in the rectangular direction along *CD* (position II) causes no change of appearance. In a few cases, however, a narrow strip, parallel to the bands mentioned above, shows compensation in position II, at right angles to that of the broad strips (fig. 4). When pits occur on such a strip, they have not the same orientation as those on the broad strips adjacent, but are arranged symmetrically with respect to the line of contact, as explained below. Thus, as regards compensation and etching, these narrow strips have the character of lamellae in twin-position with respect to the rest of the area, the twin-plane being parallel to a face of the cube (cf. fig. 2).

Form and orientation of etching pits on C-areas.—The etching pits on the *C*-areas are seen to vary in outline—even on the same strip (fig. 4). The smaller ones, which are very well defined, and appear transparent, with flat bottoms, are always clearly rhombic in outline; while the larger ones, which are bounded by four faces of a pyramid and are often opaque, are frequently square or rectangular.

The pits observed by Baumhauer and Ben Saude on similar areas were described as rhombic, either with one pair of sides parallel to the cube-edge (Ben Saude) or with their diagonals parallel to those of the cube-face (Baumhauer). A variation in form somewhat similar to the above seems, however, to have been noticed by Baumhauer on crystals from the Nikolaje Maximilianovskoi mine.²

In order to determine the true form and orientation of the pits,

¹ Cut with its length parallel to the axis of the quartz crystal.

² H. Baumhauer, *Zeits. Kryst. Min.*, 1880, vol. iv, p. 197.

a number of the sharpest were drawn by means of a Zeiss-Abbe drawing apparatus, with a magnification of about 1,300 diameters. The figures thus obtained were from 5 to 10 mm. in breadth. Each edge was drawn several times in succession with the help of a small straight-edge laid along it, and only those drawings were measured which appeared satisfactory as regards parallelism of the successive lines and of opposite edges. The sides of eight of the best figures were produced, and the angle between them bisected. The inclination of the edge of the pits to the side of the strip was then found to vary from $-\frac{1}{4}^{\circ}$ to $+7\frac{1}{2}^{\circ}$, while that of the bisecting lines (or diagonals of the rhombs) only varied between $44\frac{1}{2}^{\circ}$ and $46\frac{1}{2}^{\circ}$. Thus, while the angles of the pits vary between 88° and 75° , their diagonals do not deviate from the diagonals of the cube-face by more than $1\frac{1}{2}^{\circ}$ —an amount which, in view of the difficulty of measuring such small figures, probably does not exceed the errors of measurement. The symmetry of all the pits would therefore appear to be the same, notwithstanding their difference in form.

On a few of the narrow strips which are compensated in the second position, etching pits have been observed, and found to have their longer diagonals in the reversed position (fig. 4). It is difficult to get reliable measurements, owing to the rarity of the twinned lamellae which show pits; but in the single case measured the inclination of an edge of the pits to the edge of the lamella was:—

for two pits in the normal position $+5\frac{1}{2}^{\circ}$ and $+8\frac{1}{2}^{\circ}$;

for a pit on the twin-lamella $-5\frac{1}{4}^{\circ}$.

The inclinations of the corresponding diagonals were, respectively, 45° , 43° , and $41\frac{1}{2}^{\circ}$.

Compensation by the quartz-wedge always occurs when the wedge is inserted along the shorter diagonal of the rhombic pits.

Nature of the narrow bands on C-areas.—The fluted appearance, mentioned above as noticeable when the plate is illuminated obliquely, is seen equally well after removing the analyser, provided that the principal plane of the polarizer is parallel to the plane of vibration of the ray most strongly refracted by the plate. This suggested that the appearance might be caused by total reflection at the surface of the thin sheets, and that these might possibly be only lamellae in twin-position, like the others, but too thin to show compensation by the quartz-wedge.

In order to test this assumption, a plate (fig. 3) was mounted on a goniometer with its own plane and the trace of the lamellae parallel to the turning-axis, and examined in a beam of parallel light from a collimator, by means of a microscope fixed opposite the collimator, the

plane of vibration of the light being controlled by a nicol prism. Starting with the plate perpendicular to the line of sight (and the plane of the lamella, consequently, parallel to this line) the whole area appeared bright. On rotating it (in either direction), the appearances varied according to the plane of vibration of the light.

(1) If this plane was parallel to the plane of vibration of the *most* strongly refracted ray in the broad strips, a dark shadow (causing the fluted appearance) appeared on one side of the lamella, increased in width, became reddish, and finally vanished, the whole area becoming again transparent.

(2) If it was parallel to the plane of vibration of the *least* strongly

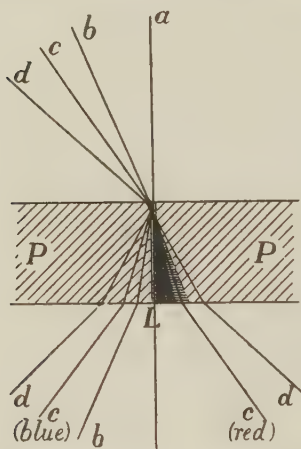


Fig. 5.—Total reflection of light by twin-lamella of low refractive index.

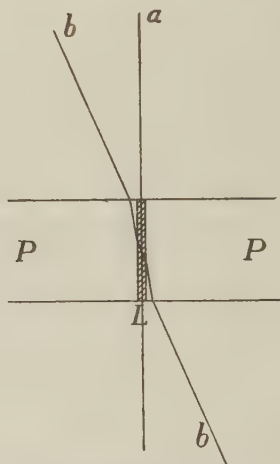


Fig. 6.—Transmission of light through twin-lamella of high refractive index.

refracted ray, no shadows appeared, and the plate remained bright throughout.

The effects to be expected from total reflection from a twin-lamella may be seen from figs. 5 and 6. Let PP represent a section of the crystal-plate by a plane perpendicular to the turning-axis, and L a twin-lamella; and let the direction of the incident light as the crystal is rotated be, successively, a, b, c, d .

If the nicol prism be so set that the refractive index of the plate is higher than that of the lamella (fig. 5), rays parallel to b will be reflected by the latter, which will cast a shadow. Of the light incident along c , the blue will be totally reflected, while the red will pass through,

and the shadow cast will appear red. For an angle of incidence corresponding to d , all colours will be transmitted.

If, however, the refractive index of the lamella is higher than that of the plate, there will be no total reflection (except for rays incident on the outcrop of the lamella, which may be neglected¹) and no shadow will be cast.

Thus, the observations agree with the assumption that the narrow bands visible in *C*-areas are lamellae of the same material as the rest of the crystal, in twin-position about a plane perpendicular to *C* and parallel to the faces of the cube, and differing only in width from the broad lamellae showing etching pits.²

By way of verification, when the plate was set to give red shadows, the microscope was turned so as to view the rays reflected from the lamellae, and the light was found to be blue and polarized, the vibrations being in the direction corresponding to the maximum refractive index of the broad strips.

Etching pits on M-areas.—Under a magnification of 1,400 diameters, the linear etching pits are seen to have the form shown in fig. 7, *A-D*. They are bounded by four sloping triangular faces, of which the two lateral ones appear dark, while those at the ends are transparent. The ends of the pits, which are rounded and difficult to see, owing to the slight inclination of the faces, are sometimes at right angles to the length of the pit (as at *A*), and sometimes inclined to it (as at *B* and *C*), indicating the presence of not more than one plane of symmetry perpendicular to the plate. Occasionally the two ends are inclined in the *same* direction, as at *D*; in which case there would be no plane of symmetry. All these forms may occur on the same homogeneous lamella.

A cube-face showing linear pits over the greater part of its surface is sometimes traversed by a diagonal line of junction, on either side of which the pits are mutually at right angles (fig. 7). A uniform *M*-area with pits parallel to one cube-edge occasionally encloses a narrow diagonal strip with linear pits parallel to the other edge. The plane of contact appears, on altering the focus, to be perpendicular to the surface of the plate.

¹ Slightly oblique rays falling on the outcrop, would be repeatedly reflected internally through the lamella to emerge at the other side of the plate, and might account for the extra brightness of the narrow bands noticed on p. 164, and for their failure to show compensation.

² This has since been confirmed by the discovery of minute rhombic pits in twin-position on a few of the narrow bands.

On *M*-areas there are also frequently seen narrow straight bands, similar to those on *C*-areas, running parallel to the linear pits. These are also shown in fig. 7, where the solid lines indicate bands which are in focus at the same time as the pits, and consequently crop out at the surface, while the dotted lines indicate bands which are sunk below the surface of the plate. These bands also represent lamellae perpendicular to the cube-face, as is evident on altering the focus or on tracing them across the edge on to an adjacent cube-face, where they are seen to be identical with the narrow bands on the *C*-areas. Whether emerging at the surface or not, these are all sensibly parallel to each other within the errors of observation, as are also the diagonal lamellae. In the crystal represented in fig. 7, the angles between the vertical, diagonal, and

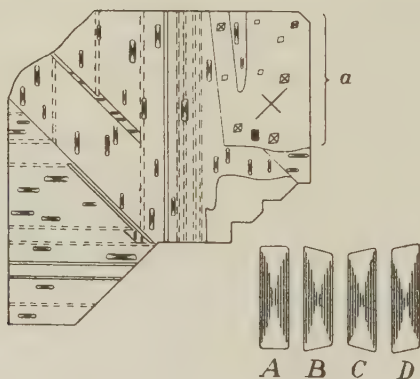


Fig. 7.—Perovskite : plate parallel to cube-face, showing oblique junction of *M*- and *C*-areas, and cubic and diagonal lamellae. *A*–*D*, forms of etching figures on *M*-areas.

horizontal lamellae do not differ from 45° , on the average by more than $\frac{1}{2}^\circ$.

On examining a plate of this kind in parallel light from a collimator, as described above, the diagonal junctions and lamellae, as well as those parallel to the cube-edges, show no sign of total reflection when the crystal is rotated, and are almost invisible except between crossed nicols. This is sufficiently accounted for by the fact that an optic axis is normal to the *M*-areas, so that for rays at a slight inclination to this direction the refractive indices of the two sets of lamellae would be nearly equal.

Junctions between C- and M-areas.—Where an *M*-area is in contact with a *C*-area, the line of junction is commonly not quite parallel to

a cube-edge, but inclined to it at an angle varying from $4\frac{1}{2}^{\circ}$ to 8° , the inclination being always towards the shorter diagonal of the rhombic pits on the *C*-area (figs. 3, 7, and 8). In a few cases, however, apparently parallel junctions have been observed (fig. 8, at *z*).

Examination in convergent light.—The interference-figure seen through the *M*-areas in convergent light is quite constant and characteristic; consisting of the well-defined circular rings, in the centre of the field, and straight black brush with strongly coloured edges, which indicate the perpendicular emergence of an optic axis of a biaxial crystal with wide axial angle and considerable axial dispersion. The plane of the optic axes is in all cases perpendicular to the length of the linear etching pits. The brush is coloured red on the side towards the positive bisectrix. The colours are usually on the same sides of the brush over the whole of an *M*-area, but here and there a strip may show them in the reversed position, as they would be in a lamella in twin position about a cube-face. This is in accordance with the observed uniform character of the *C*-areas, in which only occasional strips (other than the narrow bands) occur in twin position.

On examining in convergent light a *C*-area fairly free from fine lamellation and showing uniform extinction, two brushes sweep symmetrically across the field, meeting in the centre (as they would do in a plate of crystal perpendicular to a third mean line); but even with sodium-light no interference-bands are visible, although the plate may be perfectly transparent, and (but for the lamellae) apparently homogeneous.

On tilting the plate in a plane containing its normal and one of its extinction-lines, i.e. in a plane parallel to a cube-diagonal, no bands come into view, and owing to the narrowness of the lamellae the light is soon cut off by total reflection. Even on tilting in a plane parallel to one of its edges, so as to bring one of the optic axes towards the line of sight, no rings become visible.

An attempt was made to eliminate any disturbance caused by lamellae by selecting a small fragment of an etched crystal, as free as possible from them, and grinding it down into a small rectangular prism about $\frac{1}{2}$ mm. in length, bounded by three natural cube-faces (in a zone), one of which showed linear pits, and three polished surfaces.

When mounted on the stage-goniometer, the etched face, and that next it, showed in convergent light each a perfectly normal interference-figure corresponding to a biaxial optic axis emerging perpendicularly. Similar figures were visible through the parallel faces, on rotating the prism.

All the optic axes showed strong dispersion, the brush being strongly coloured (red and blue) on its edges, and the red being always on the positive side of the figure. The appearance and relations of the four figures was quite normal, and there was no indication of a dispersion of the bisectrices which would indicate less than orthorhombic symmetry. In the intermediate positions, however, in which the bisectrices should have been visible, the figure always disappeared and no figure corresponding to a bisectrix could be seen. This may perhaps have been due to the high refractive index (about 2.4),¹ which would cause a considerable amount of refraction (or total reflection) at the corner of the crystal, even when the latter was immersed in cedar oil ($\mu = 1.516$); or it may possibly be due to a few lamellae, traces of which were visible through the faces parallel to the axial plane. Through the pair of faces parallel to the axial plane, two symmetrical brushes, but no interference-bands, are visible in sodium-light.

The *C*-area marked *a* in the corner of the plate shown in fig. 7, which appears to be quite free from lamellae, was also examined on the stage-goniometer under the microscope. When the plate is horizontal, it shows a pink of the fifth order, and this colour does not change when the plate is inclined as much as 60° in either direction, which would correspond to an inclination of the ray within the crystal of about 21° to the plate-normal. In convergent sodium-light no rings are visible, but when the plate is horizontal two ill-defined brushes appear to meet symmetrically in the centre of the field.

The form and relative orientation of the etching pits, as well as the optical characters of the plates parallel to the cube, as observed above, are in accordance with Baumhauer's view; but, as will be seen on comparing figure 1 with figures 3 and 7, the linear pits do not lie at right angles to the junction between *C*- and *M*-areas (as in fig. 1) but in all cases (approximately) parallel to them. This point will be referred to later (p. 173).

Plate parallel to g (320)?

A plate cut parallel to the face *g* (320) (cubic form) mentioned on p. 161, shows through the greater part of that face a series of parallel strips, inclined at about 10° to its intersection with the cube, as shown in fig. 8. The vertically shaded portions of the face *g* show definite extinction in the direction of the lines of shading, and, with convergent

¹ As determined by means of a prism of about 45° made by polishing a cube and a dodecahedron-face on the same small fragment.

light, the emergence of a negative bisectrix of wide axial angle, the optic axial plane being horizontal, and the bisectrix inclined somewhat to the face-normal in that plane. These appearances agree with the assumption of an optic axis emerging perpendicular to each of the adjacent cube-faces, the bisectrix being perpendicular to the face of the dodecahedron; and on turning the crystal so that the face m' is horizontal an optic axial figure of the usual type is visible, the brush being coloured blue on the side towards the negative bisectrix, as in other cases. When g is horizontal, the shaded portions of the adjacent cube-faces, m and m' , also show extinction along the lines of shading.

The strips are the outcrops of lamellae, which, on rotating the crystal, are seen to dip into the face g at about 68° . The junctions can be traced across the edges on to the triangular face d , and further on to the cube-face c , on which (though rather indistinct) they appear to run parallel to the edge c/m . On the face m' they make an angle of 8° with the cube-edge, and the lamellae are consequently parallel to a plane in the zone $[cm]$, inclined at about 8° to m . The traces upon c of a few of the junctions, however, are slightly inclined (10° – 12°) to the edge c/m .

The alternate strips on g show two types of etching figures, A and B . Those parts of the face which are shaded exhibit pits resembling A , while on other parts the pits are of type B , though some (near p) are much more elongated. The relations of these pits to each other and to those on the adjacent cube-faces are as indicated in the figure. The orientation of each type is the same throughout.

The lamella r is sufficiently thick to intersect both the face g and the cube-face m' . On the former it shows A -pits, and on the latter vertical linear pits (M -area) and a normally emergent optic axis, as mentioned above.

On the cube-face, at t , is a strip of C -area, representing the outcrop of a lamella parallel to the others, and showing the same relation to the adjacent M -areas as was previously described (p. 168). But at z are some small C - and M -strips whose junctions are *parallel* to the cube-edges.

At v are seen pits of type B , and on the adjacent cube-face, at w , the pits are rhombic (C -area), the relative orientations being as shown. The areas v and w appear to belong to a single lamella.

The relation between the rhombic pits at x and the B -pits shown at p is incompatible with that of the pits at v , w . This point is referred to below (p. 174).

Some of the lamellae (such as r , s , t) enclose narrow bands parallel to

the cube-edge, and evidently identical with those seen in plates parallel to cube-faces.

Plate parallel to an octahedron-face.

A plate parallel to an octahedron-face on the corner of a cube with truncated edges, shows on that face monosymmetric etching pits of the form and orientation indicated in fig. 9. The face is surrounded by

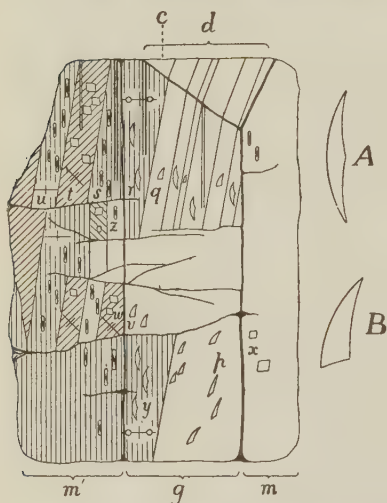


Fig. 8.—Perovskite : plate parallel to g (320), showing lamellae and etching figures upon g and upon the adjacent cube-faces.

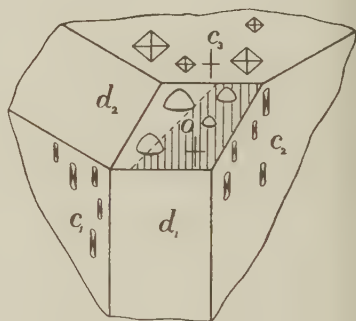


Fig. 9.—Perovskite : section (free from lamellae), parallel to octahedron-face (o), showing etching figures upon o and upon the adjacent cube-faces.

three faces of the cube and two of the dodecahedron, indicated by the letters c and d respectively.

With transmitted light the plate shows extinction, on the shaded portion, parallel to the lines of shading, and is compensated by a quartz-wedge at right angles to these lines. The want of extinction on the unshaded portion is due to a subjacent layer near the under surface of the plate.

The whole face, and the parts of the surrounding faces adjacent to it, appear uniform and free from lamellae. The dodecahedron-faces show no clear pits, but the three cube-faces exhibit well-defined pits of the forms shown. Of the two former, d_1 is bright, but d_2 rough with crossing furrows.

The angles between the faces of this crystal were measured on the goniometer, with the help of the attachment described in the succeeding paper. Sharp reflections were obtained from the faces c_2 , c_3 , o ; and c_1 , though vertically striated, gave a reliable reading in the zone $[c_1c_3]$. The following values were obtained: c_1c_3 $89^\circ 55'$, c_2c_3 $89^\circ 58'$; oc_3 $54^\circ 35'$, oc_2 $54^\circ 38'$.

III. DISCUSSION OF RESULTS.

It will be seen that the crystals from the Burgumer Alp agree closely in their structure and optical characters with those from Zermatt and the Urals described by Baumbauer and (except in the orientation of the rhombic pits) by Ben Saude, and do not show any of the peculiarities previously found in crystals from this locality.

The definiteness and regularity of the structure and etching figures, and of the optical characters, together with the constant relations existing between them, appear to the author to exclude the possibility of their being caused by strain in a cubic material, and to indicate that the crystals really belong to one of the biaxial systems—most probably to the orthorhombic system, as supposed by Des Cloizeaux and by Baumbauer. The detailed explanation, indeed, proposed by the latter (p. 158), appears sufficient to account for almost all the phenomena observed in the crystals above described, as well as those of the crystals from Zermatt and the Urals, as may be seen on comparing the description with the figures given on p. 160.

The fact that in plates parallel to the cube-faces, which show C - and M -areas in contact with one another, the linear pits are parallel to the line of junction (or nearly so) instead of perpendicular thereto, as described on p. 170, might be explained on the supposition that the crystals, while in twin position about (111) , are not in contact along this face but along a plane near $(1\bar{1}0)$; but the relation may be more naturally expressed as resulting from a rotation through one quarter-turn about the pseudo-tetragonal axis perpendicular to (110) , on the principle laid down by Mallard. The contact is usually along a plane slightly inclined to the cube-face, the lines of junction of the C - and M -areas being inclined to the cube-edge, in the direction of the shorter diagonal of the rhombic pits, at angles which vary between $4\frac{1}{2}^\circ$ and 8° , but occasionally (on the crystal shown in fig. 8) are zero.

The plane of contact does not appear to have rational indices (in which respect it resembles the 'plane of rhombic section' of the plagioclase feldspars), or even to lie in a definite zone, as the inclination of its traces on two adjacent faces of the cube is not necessarily the same. In this case the plane bears a different relation to the two individuals. The constant parallelism of narrow bands occurring in lamellae with this kind of contact (as in fig. 3, *b, d, e*, and fig. 8, *r, s, t*) shows, however, that the twin relation is always the same and is independent of the direction of the plane of contact.

Although none of the plates examined have shown linear pits at right angles to a *C-M* junction, the occurrence of diagonal junctions, with pits mutually perpendicular on the two sides, and the plane of contact apparently perpendicular to the cube-face (as in fig. 7), can only be accounted for by the assumption of twinning on a face of $\{111\}$ with contact along the twin-plane, as described by Baumhauer.

The twinning observed is thus precisely what might be expected to occur in a pseudo-cubic substance, viz. twinning by (i) one half, or (ii) one quarter-turn about the pseudo-tetragonal axis perpendicular to *M* (110), contact in (i) being along (110) and in (ii) along a plane slightly inclined to this face; (iii) one half-turn about the pseudo-digonal axis perpendicular to (111), with contact along this face.

As regards the etching figures on faces other than those of the cube, which have not been previously described, it may be pointed out that of the pits observed on the face *g* (fig. 8), those of the form of *B*, which are adjacent to a cube-face having rhombic pits, show the absence of symmetry proper to a face of an orthorhombic pyramid. Those having the form of *A*, which are adjacent to a cube-face with linear pits, have the monosymmetric character proper to the faces of an orthorhombic prism. The indices of this would be $\{510\}$.

If we admit that the areas *v* and *w* belong to the same lamella, the relation between the various areas on this crystal are in accordance with the laws of twinning stated above. Thus the lamellae *r, s, u*, &c., would be in parallel position and separated by the lamellae *t, q*, &c., in twin position. The discrepancy between the relation at *vw*, and that at *px* might be due to the existence of a twin junction between *p* and *x*, with twin-plane parallel to that face of $\{111\}$ which is nearly perpendicular to *p*, or possibly to the fact that since the angle *mg* (56°) is not equal to *m'g* (33°), the area at *p* would represent a different form from that at *v*, and might therefore naturally have different pits. The indices of the various areas would be as follows: *twx* $\{001\}$, *su*

$\{110\}$, $ry\{510\}$, $qv\{223\}$, $p\{332\}$. Unfortunately this part of the crystal was damaged, so that this question could not be settled.

The evidence for orthorhombic symmetry afforded by the etching figures and optical characters of the crystal-corner shown in fig. 9, which is unusually free from complication by lamellae, is, however, particularly striking. The characters are, in fact, precisely those which should be found in an orthorhombic combination of (001) , (110) , $(\bar{1}10)$, and (021) .

On the other hand, though it is hardly justifiable to draw conclusions from a single crystal, it should be noted that while the angles c_1c_3 and c_2c_3 (fig. 9) are very nearly 90° , the angles oc_3 and oc_2 differ considerably from the cubic angle, $(100) : (111) = 54^\circ 44'$. The angle oc_1 would therefore also be different, and would not be equal to oc_2 . If this difference should be confirmed, the symmetry could not be orthorhombic.

It may also be mentioned that on a very finely lamellated C -area, at a in fig. 3, which consists of alternate lamellae of about equal breadth in twin position, the lamellae are not extinguished simultaneously at exactly 45° to the cube-edges, but in two sets, as in a plagioclase feldspar; and that the extinction-positions of these are not symmetrical to the junctions (cube-edges), the measured angles being $42\frac{1}{2}^\circ$ and 48° respectively. This again would, if confirmed, indicate that the symmetry is less than orthorhombic; and the same is true of the etching pits of the form D (fig. 7).

It is thus possible that perovskite may ultimately have to be referred to the monoclinic or anorthic system; but so many of its characters point to orthorhombic symmetry that it may for the present be considered to belong to that system.

The absence of interference-bands from C -areas does not appear to be due to the overlapping of layers in non-parallel position, since it is noticeable in thin as well as in thick plates.

The crystalline characters of perovskite may be shortly stated as follows:—

System: Orthorhombic? (pseudo-cubic).

$$a : b : c = 1 : 1 : 0.7071.$$

Principal forms: $M\{110\}$, $C\{001\}$ = 'cube.'

$a\{100\}$, $b\{010\}$, $\{111\}$ = 'dodecahedron.'

$\{201\}$, $\{021\}$ = 'octahedron.'

$\{510\}$, $\{223\}$, $\{332\}$ (?).

The crystals always show a lamellated structure due to twinning, (i) by a half-turn about the normal to (110), (ii) by a quarter-turn about the same line, (iii) by a half-turn about the normal to (111).

Plane of the optic axes parallel to $C(001)$. $2V=90^\circ$ (about). Negative bisectrix (α) perpendicular to (100). Dispersion of the optic axes, strong; about the positive bisectrix $\rho > v$. Birefringence moderate, $(\gamma - \alpha) = 0.017$ (measured by compensation of a plate with rhombic pits; see p. 164).

With regard to the cause of the cubic form, the lamellated structure at once recalls that of leucite, and suggests strongly that, like it, perovskite may be dimorphous. This explanation has already been proposed by several authors; but, so far, there is no direct evidence of the existence of a cubic variety of perovskite.

Ben Saude, indeed, noticed that after heating to redness the outline of the optically dissimilar areas had slightly changed.¹ This might have been due to dimorphism; but similar changes of twin-structure have been observed to take place in polysymmetric substances—as potassium sulphate—without change of state. On the other hand, Brauns² found that no difference could be detected in the optical properties of a crystal, of which one-half was heated to redness.

As an argument against the existence of polymorphism in perovskite, Ben Saude mentions the fact, noticed by Hautefeuille, that artificially prepared crystals are doubly refracting. It seems quite possible, however, that a change of state might occur during the process of cooling of crystals which were originally cubic, at the temperature and under the conditions of formation.

In conclusion, the author desires to express his gratitude to Professor von Groth, at whose instance the work was undertaken, for the loan of the material and for much kindly interest and advice while he was working in his laboratory in Munich.

¹ Loc. cit., p. 27. The fact that on the areas which had suffered change by heating the pits remained unaltered in form, was mentioned by Ben Saude as showing the unsuitability of etching figures for the determination of symmetry. Since, however, the pits only indicate the nature of the structure existing at the time when they were formed, they could not (as has been pointed out by Ewing, Proc. Roy. Soc., 1900, vol. lxvii, pp. 112–117, in the case of etched surfaces of metals) change their shape owing to a subsequent alteration of that structure. Had the crystals been re-etched, there can be little doubt that the new figures would have tallied with the altered optical properties.

² R. Brauns, 'Die optischen Anomalien der Krystalle.' 1891, p. 349.

COMMUNICATIONS FROM THE OXFORD MINERALOGICAL
LABORATORY. No. XIII.

An attachment to the goniometer for use in the measurement of crystals with complex faces.

By H. L. BOWMAN, M.A.

Demonstrator of Mineralogy in the University of Oxford.

[Read March 17, 1903.]

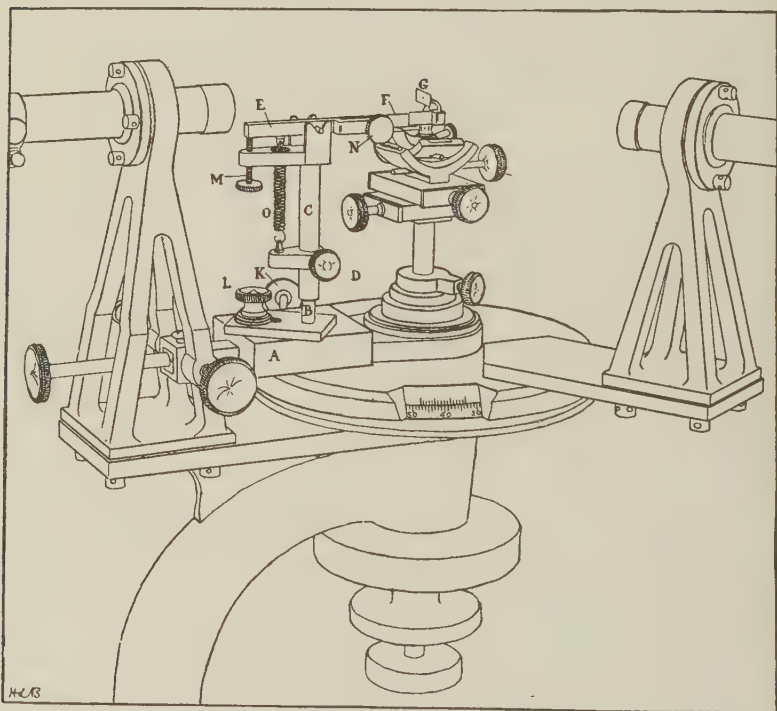
WHEN mounted for measurement on the goniometer, the faces of the perovskite crystals described in the preceding paper yield, owing to the complex lamellated structure, a confused mass of images of the signal which cannot be analysed by the ordinary methods (such as using a lens in front of the eyepiece or shading portions of the face with a screen held in the hand), on account of the number and extremely small size of the reflecting surfaces. The apparatus described below was designed to give the means of identifying with certainty the image reflected from any given portion of such a face, and has been found to answer this purpose satisfactorily.¹

It consists of an adjustable support carrying a perforated diaphragm between the collimator and the crystal, so as to cut off the light from all except the desired area. Since in order to isolate minute lamellae the aperture must be very small, the screen must be placed close to the crystal, so that it may not cut off the extremities of the image. On this account also it is convenient to use a small square or circular hole as signal, instead of the usual slit.

The support consists of a flat base *A*, clamped to the frame of the goniometer in any convenient manner. (In the drawing it is shown in position on the goniometer figured in Professor Miers's 'Mineralogy' (1902), p. 105, on which it is fixed to the arm of the telescope-clamp by the screw *K*.) Upon the base rests a slotted plate,

¹ The instrument was constructed for me by Mr. S. W. Bush, of the University Museum.

which carries the vertical rod *B* and can be clamped in any position by means of the screw *L*. This, with a sleeve *C* sliding on the rod, to which it is clamped by *D*, gives means of rough adjustment in horizontal and vertical directions. Fine adjustment in height is provided for by the arm *E*, which is supported in the centre on trunnions turning in Y's at the top of *C*, and at the end on the point of the fine screw *M*, and is kept in place by the spring *O*. Fine adjustment in the horizontal plane is given by the flat spring *F*, which forms a prolongation of the



arm *E*, and carries at its end a socket to receive the shank of the screen *G*. The spring rests against the point of the fine screw *N*, which passes through the slightly bent end of *E*.

The screen is made of thin metal foil, in which holes of the required size have been made with a fine needle. It is placed as near as possible to the crystal (with a small crystal it may be within a millimetre or less), and the screws *M* and *N* then enable it to be moved about with perfect steadiness or held in any position.

Using holes of $\frac{1}{10}$ to $\frac{1}{20}$ mm. diameter sharp images can be isolated from a confused blur, which are due to a lamella whose thickness is no greater than this, provided the surface of this is plane. The exact position of the illuminated area giving the reflection can be readily determined when the crystal is examined with the help of the lens in front of the object-glass, since the reflection of the aperture in the crystal face is in focus practically at the same time as the latter. The small angle between the faces of adjacent lamellae may be easily found on traversing the screen by means of the slow-motion-screws.

OBITUARY.

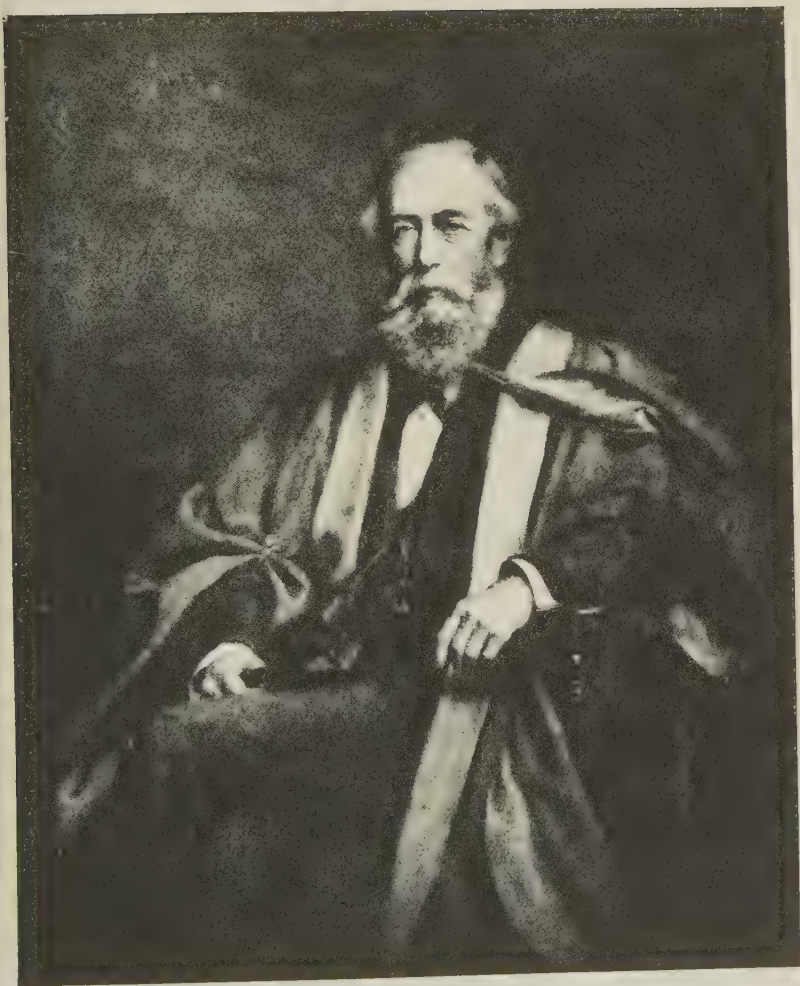
HENRY CLIFTON SORBY (1826-1908).

(With a Portrait,¹ Plate VI.)

IN the important work of demonstrating how the internal molecular structure of minerals is revealed by their action upon light passing through them, two British mineralogists—Brewster and Sorby—were among the foremost pioneers. In the more than three hundred papers of Brewster, written between the years 1815 and 1869, there will be found the records of researches upon almost all the common transparent minerals, and on not a few rare ones. But Brewster's work was to some extent limited by the necessity he was under of obtaining for his investigations well-crystallized specimens, from which moderately thick slices could be cut in definite directions. To Sorby remained the merit of showing how the optical method could be applied to the minute, irregular particles of minerals building up rocks, even when exposed in very thin sections and cut at indefinite angles.

Sorby had as a schoolboy imbibed a taste for science, which was fostered by a mathematical tutor under whom he was placed after leaving school. This tutor, the Rev. Walter Mitchell, author of the treatise on Crystallography in Orr's 'Circle of the Sciences' and of some original papers on the same subject, had been a medical student, and was able to instruct Sorby in chemistry and anatomy as well as in various branches of physics, and when only twenty years of age Sorby published his first scientific memoir. In the year 1849 Sorby, having learned the art of making thin sections of hard materials from his friend William Crawford Williamson, conceived the idea of applying the method to the study of the small, mineral particles building up rocks. In 1850, a paper which he wrote on 'The calcareous grit of

¹ The accompanying plate (Plate VI) is reproduced from a portrait, painted by Mrs. M. L. Waller, which was presented to Dr. Sorby by the Sheffield Literary and Philosophical Society in commemoration of his fifty years of connexion with the Society. It first appeared in the 'Naturalist' in 1906, and the block has been lent by the courtesy of the editor and publishers of that journal. The portrait represents Dr. Sorby at the age of 71, and a duplicate of it was deposited in the University of Sheffield. Excellent reproductions of the portrait were sent by Dr. Sorby to his friends, who signed an address to him at the time of the centenary of the Geological Society, only shortly before his death.—L. J. S.



H. C. Lovell

the Yorkshire coast' afforded him the opportunity of showing the value of the method. He effected a complete mineralogical analysis of the rock, identifying the quartz, calcite, and chalcedony by optical methods—both plane and circularly polarized light being employed; he separated the several ingredients by chemical and mechanical means, and he determined the proportions of each in the rock.

About this time, too, Sorby appears to have been greatly struck by the phenomena of polymorphism. The relations of calcite and aragonite in shells and in rocks then, and frequently in after life, were made the subject of experiment and speculation. He also investigated what he regarded as evidence of 'tetramorphism' in carbon; and if mineralogists do not now accept all his conclusions on this subject they cannot but be impressed by the refinement of his methods and the ingenuity of his reasonings.

Pseudomorphism was another question that at this time engaged much of Sorby's attention, and he often returned to the subject in after life. Important memoirs written by him in 1856 showed that great rock-masses like the Magnesian Limestone and the Cleveland ironstone owed their origin to pseudomorphous conversion of the calcite of ordinary limestones into dolomite and chalybite respectively. Experiments consisting of placing calcite crystals into various solutions were commenced at this time, and Sorby was able to watch the operations for more than half a century, some of the specimens being now left by his will to the Sheffield Museum.

While preparing and studying the thin sections of many aqueous, igneous, and metamorphic rocks, the attention of Sorby was naturally drawn to the existence in the crystallized minerals of innumerable cavities containing various liquid and solid substances. On December 16, 1857, he brought before the Geological Society his epoch-making memoir 'On the microscopical structure of crystals'—a memoir which, though neglected, and even ridiculed at the time, laid the foundation of microscopical petrography—and, in doing so, widened enormously the sphere of influence of mineralogy from which it borrowed so much. It was in German scientific literature that we find the first application and development of Sorby's ideas; but French and British workers gradually took up the work—Zirkel, Renard, and David Forbes soon becoming conspicuous among the friends and disciples of Sorby who were prepared to follow and were always ready to defend his method.

In 1877 Sorby wrote for this journal an interesting obituary of his friend David Forbes, and it is impossible at the present time to read

this notice without being struck by the contrast between the scientific careers of the two men. Forbes was called upon, while still very young, to seek his fortune by taking charge of mining work in a foreign country; his short and active life, full of travel, adventure, and peril, was exposed to frequent accident and disease; yet, while accumulating wealth, he lost no opportunity of advancing scientific knowledge, and found time to study rocks by Sorby's method and to follow to some extent in his footsteps; born two years after Sorby, Forbes, as the victim of many hardships, predeceased his friend and master by more than thirty years. Sorby, on the other hand, inherited from his father a sufficient fortune, which contenting him through life, he steadily resisted every temptation that might distract him from the great work of scientific research to which he regarded his life as dedicated; he considered the care of his health and the avoidance of pleasures and occupations that would interfere with his studies as duties which he owed to science; and, though his end was probably hastened by an accidental fall, he lived to an advanced age, retaining till within a few hours of his decease his interest in and capacity for scientific investigation. Sorby, in writing upon the advantages to a scientific man of being free from business or professional cares, says, 'I am thankful to say that complete immunity from such routine employment has been my own happy lot.' Never, indeed, did a man make better use of his opportunities!

It was a characteristic of Sorby's mind to prefer seeking for new truths rather than following up the pursuit of lines of investigation already discovered. Hence the wonderful versatility of his genius. But though neglected for a time, the old fields of research were again and again revisited by him. Thus in 1869, returning to the study of the cavities of minerals and the nature of their liquid contents, he was able to show that in many minerals, including gems, carbon dioxide in a liquid state is frequently present in 'the sealed flasks of crystals', as Julien has so aptly styled these cavities. Our own journal shows how, especially between 1877 and 1879, Sorby returned to the consideration of methods of determining the optical constants of minerals in thin sections.

Sorby's work naturally led him to ponder deeply on the conditions under which minerals and rocks must have been formed. His early papers on the origin of cleavage and foliation are admirable illustrations of the results to be obtained by a combination of experiment and observation. His more general conclusions on the subject are elaborated in his Bakerian lecture 'On the correlation of chemical and mechanical

forces'; and various applications of his views on the subject are made in his experimental work on fused rocks and his memoirs on 'cone-in-cone' structure and on 'impressed pebbles'.

In 1863 the application of his method to the study of meteorites led Sorby to investigate the nature of the iron-nickel alloys in them, by examining etched surfaces under the microscope. Not only did this lead to many interesting scientific results, but in the end resulted in discoveries of far-reaching importance to the industries of his native town of Sheffield. In the various artificial products which he studied Sorby showed the presence of pure iron in interlacing cubes and octahedra, of an intensely hard constituent (now known as 'cementite'), and of the pearly material (now called 'pearlite'). He thus laid the foundation of new methods of metallurgical study, which have been so fruitful of results in recent years.

In 1865 Sorby commenced his interesting investigations based on the adaptation of the spectroscope to microscopic work, among which we must notice his studies of the spectra of jargoon and other gems and coloured transparent minerals.

During the earlier years of his life Sorby's work was almost wholly carried on in his Sheffield homes—at first at Woodbourne and afterwards at Broomfield. But after the death of his widowed mother, to whom he was devotedly attached, he began to take a more active part in the scientific work of London. From 1876 to 1879 he was our first president; from 1878 to 1880 he was president of the Geological Society; and from 1875 to 1877 he presided over the Royal Microscopical Society. In 1875 he bought a yacht—the 'Glimpse'—and during the summer months pursued his researches on board this vessel. This change in his habits led to the adoption by him of new lines of research. Those who met him found him enthusiastic as ever in all matters connected with geology and mineralogy—but his talk was chiefly of Gothic architecture, and the mechanical and artistic methods of the ancient builders, while old books, ancient engravings, and water-colour drawing occupied much of his time. He utilized his yacht not only for visiting places of interest, chiefly in East Anglia, but also for collecting marine animals and plants, the structure and distribution of which were pleasant objects of study, while ingenious methods for their preservation and exhibition were constantly being devised by him.

In 1903 his active career was brought to a close by an accident which occasioned partial paralysis, but for nearly five years more—though mostly confined to his bed—he continued his studies and

writing, an important memoir being sent to the Geological Society shortly before his death.

He was devotedly attached to his native town of Sheffield, where so much of his life was spent. Of the Literary and Philosophical Society and other institutions in Sheffield he was a warm and constant supporter, and in the foundation of Firth College and the guiding of its evolution, first into a University College, and finally into the University of Sheffield, he was the leading spirit. All through his life he was 'the Apostle of Scientific Research', and on his death it was found that, after providing for relations and old servants and sailors, the half of his fortune was left, in part to found a chair in the Sheffield University, and in part to the Royal and Geological Societies to promote the researches which had been the object and the delight of his own life.

NOTE. In 'Unencumbered Research; a Personal Experience', published in the volume of 'Essays on the Endowment of Research' in 1876, and in a lecture, 'Fifty Years of Scientific Research,' published by the Sheffield Literary and Philosophical Society in 1897, Sorby has given many interesting particulars of his life and work. In the 'Geological Magazine', for May, 1908, I have shown how the work of microscopic petrography was originated, contrary to prevalent misconceptions on the subject. A list of Sorby's scientific memoirs, more than 250 in number, is published in the 'Naturalist' for 1906.

J. W. J.

REVIEWS.

Tables of Minerals: including the Uses of Minerals and Statistics of the Domestic Production. By SAMUEL LEWIS PENFIELD. Pp. vi + 88. 2nd edition. (New York: John Wiley & Sons; London: Chapman & Hall. 1907. Price 4s. 6d. net.)

THE first edition of this book appeared in 1903, and the present edition has been prepared after the author's death by his successor, Professor W. E. Ford, in the Sheffield Scientific School of Yale University. All the important minerals, to the number of 450 species, are tabulated (1) according to their system of crystallization, (2) according to the elements they contain, and (3) with reference to their geological occurrence and associations. There is also a short section dealing with various useful minerals under the headings abrasives, gem-minerals, ornamental stones, &c. The relative importance of the minerals listed is distinguished by differences in type, the names of the more common being printed in heavy capitals. The chemical formulae are given, and the page-references to Dana's 'Textbook' and 'System' are added for the convenience of the student. The brief statements as to the uses, amounts of production, and commercial values of different minerals emphasizes the importance of the study of mineralogy and makes the subject of more general interest. With reference to values, attention may be called to the valuation of one-carat stones, in three qualities, of each of the species of gem-minerals, this information having been supplied by Dr. G. F. Kunz. The book is primarily intended for students, but it will also be found useful for reference and as a refresher to the memory when determining minerals.

Synopsis of Mineral Characters, alphabetically arranged for laboratory and field use. By RALPH W. RICHARDS. Pp. v + 99. (New York: John Wiley & Sons; London: Chapman & Hall. 1907. Price \$1.25.)

A Pocket Handbook of Minerals, designed for use in the field or class-room with little reference to chemical tests. By G. MONTAGUE BUTLER. Pp. ix + 298, with 5 tables and 89 text-figures. (New York:

John Wiley & Sons; London: Chapman & Hall. 1908. Price 12s. 6d. net.)

THESE are small and handy books of reference which will be found useful to students and amateurs. They are neatly bound in leather, and can be conveniently carried in the pocket. The essential characters of the more important minerals are briefly stated, and simple tests by which they may be distinguished are given. In the first of them the arrangement is alphabetical, whilst in the second it is that of Dana's 'System'.

A Key for the Determination of Rock-forming Minerals in thin Sections.

By ALBERT JOHANNSSEN. Pp. ix + 542, with 107 text-figures, 1 coloured plate, and 24 diagrams. (New York: John Wiley & Sons; London: Chapman & Hall. 1908. Price 17s. net.)

THE bulk of this volume is largely accounted for by the presence of a considerable number of blank pages and by frequent repetitions in the tables. For instance, the summaries of the characters of antigorite, cordierite, and phlogopite, which each occupy one-third of a page, are repeated in exactly the same form no less than seven times. Before the book can be used it is intended that the edges should be cut along guide-lines, whereby tabs are left to indicate the grouping adopted in the determinative tables; elaborate instructions are given as to the method of so cutting the book, and coloured gummed labels are provided. Probably few persons will laboriously cut the hundreds of pages, and certainly library copies will not be cut, in which case the book is practically useless, especially in the absence of any other key to the tables than that given by the tabs.

Lengthy determinative tables of the kind attempted savour rather too much of rule-of-thumb methods, and it is extremely doubtful whether they are of much value to students, whilst it is possible that they may sometimes lead to error. Determinative tables to be of any value should be clear and concise, and for the present purpose they might very well have been condensed into a dozen pages. The lists of refractive indices, birefringences, specific gravities, and of minerals arranged according to crystal-systems, which are given at the end of the volume, are much more useful. The statements in the text of the general portion of the book are often too brief to be perfectly clear, and the student would be better advised to read J. P. Iddings's excellent *Rock Minerals* issued in 1906 by the same publisher. Several errors are to be noticed; to quote only one (or rather a double one): methylene iodide is referred to as 'Braun's solution'.

Rocks and Rock Minerals, a manual of the elements of petrology without the use of the microscope, for the geologist, engineer, miner, architect, &c., and for instruction in colleges and schools. By LOUIS V. PIRSSON. Pp. v+414, with 36 plates and 74 text-figures. (New York: John Wiley & Sons; London: Chapman & Hall. 1908. Price 10s. 6d. net.)

THE scope of this elementary treatise on macroscopic petrography is fully set out in the title quoted above, and the author's name is alone sufficient guarantee that the subject has been well handled. The matter is presented in an attractive and readable form, and the numerous illustrations, for the most part representing American occurrences, add to the interest of the volume. In addition to the descriptions of the rocks themselves, particulars are given of the forms and relations of the rock-masses from a geological point of view, and much information is added on the petrological side as to their genesis. About 100 pages are devoted to the rock-forming minerals, 150 to igneous rocks, and about 70 each to sedimentary and metamorphic rocks respectively.

The following classification, based mainly on texture and colour, is adopted for igneous rocks. It is said to be essentially the same as the 'quantitative classification' proposed in 1903 by Messrs. Cross, Iddings, Pirsson, and Washington, and if so it has clearly the advantage over the latter in its freedom from the burden of so many uncouth names.

A. Grained rocks.

(a) Felspathic rocks (with or without quartz: non-porphyritic or porphyritic).

(b) Ferromagnesian rocks (with or without felspar: non-porphyritic or porphyritic).

B. Dense rocks.

(a) Light-coloured (non-porphyritic or porphyritic).

(b) Dark-coloured (non-porphyritic or porphyritic).

C. Glassy rocks (non-porphyritic or porphyritic).

D. Fragmental material.

The main types included in this classification are: A(a), granite, granite-porphyry, syenite, and syenite-porphyry; A(b), diorite, gabbro, dolerite, diorite-porphyry, peridotite; B(a), felsite and felsite-porphyry; B(b), basalt and basalt-porphyry; C, obsidian, pitchstone, and vitrophyre; D, tuffs and breccias. Under each of these heads several related rocks are mentioned as varieties, though in many cases various kinds are grouped together (e. g. rhyolite, trachyte, andesite, and phonolite come under felsite).

Kristalltafeln. By MAX SCHWARZMANN. (Karlsruhe: G. Braunsche Hofbuchdruckerei. 1907. Price 24 Marks.)

A USEFUL set of wall-diagrams for demonstrating the forms of crystals and minerals has been prepared by Dr. Max Schwarzmänn. The sheets measure $2\frac{1}{4} \times 3\frac{1}{4}$ feet (70×100 cm.), and are mounted on linen with wooden rollers. The subjects on the nine sheets are: cubic system; systems other than the cubic; hemihedral forms; elements and sulphides; oxides; oxides, haloids, aluminates, and borates; carbonates; sulphates, molybdates, tungstates, and phosphates; silicates. Altogether, there are 113 enlarged diagrammatic sketches similar to those of the textbooks. Brief explanations of the figures are given in a small eight-paged pamphlet.

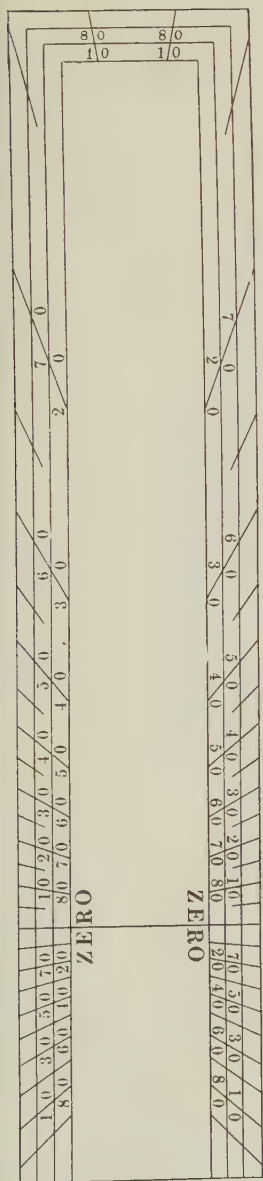


Fig. 1.

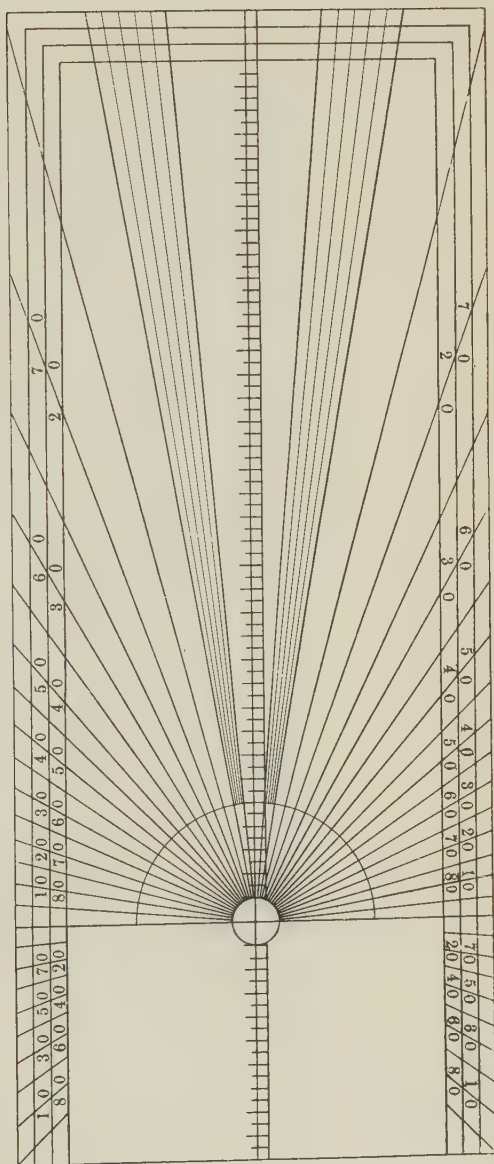
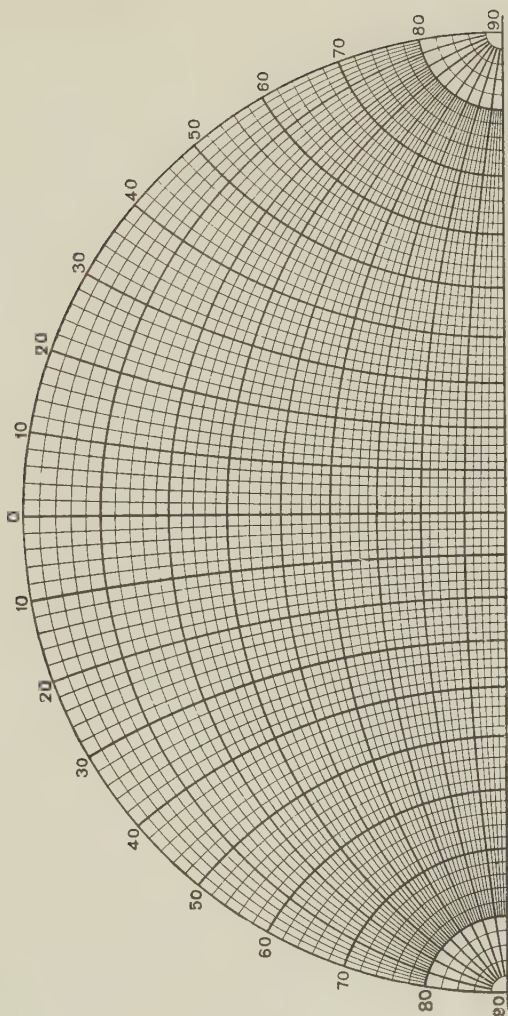


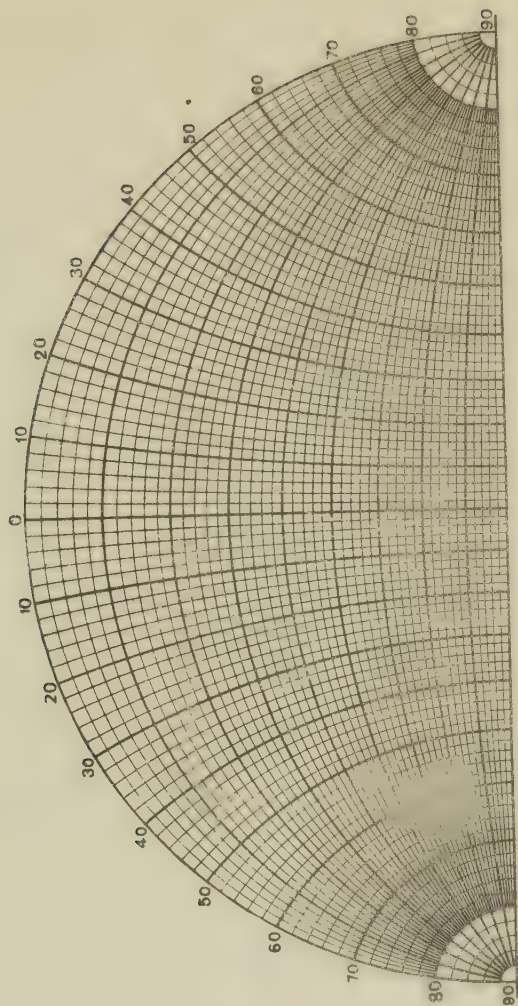
Fig. 2.

A. HUTCHINSON: STEREOGRAPHIC AND GNOMONIC PROTRACTORS.

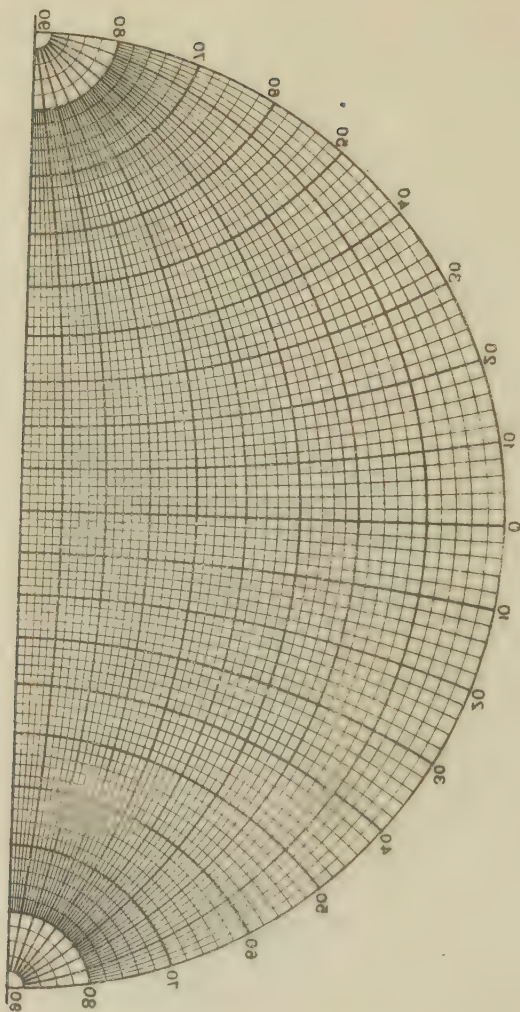
($\frac{1}{2}$ actual size. The originals are graduated to show degrees, but for the sake of clearness the finer divisions are omitted in the figures.)

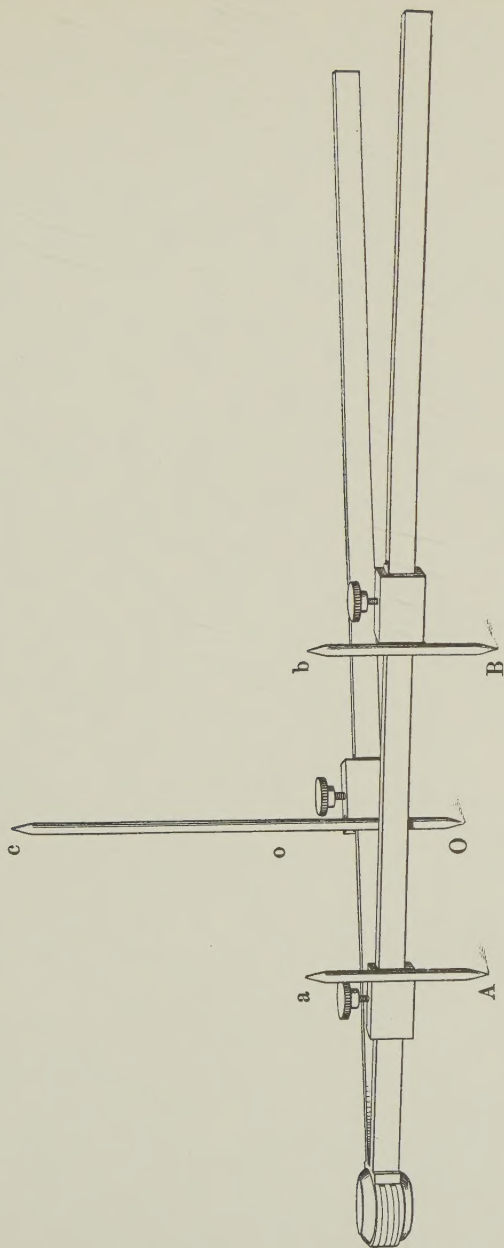


A. HUTCHINSON: STEREOGRAPHIC NET.



A. HUTCHINSON: STEREOGRAPHIC NET.





A. HUTCHINSON : TRIANGULAR COMPASS.

($\frac{1}{2}$ actual size.)

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